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A device-independent framework to classify and describe atomization is developed. This framework divides atomizers into various classes based on the geometry of the liquid prior to breakup. These classes are general enough to encompass a wide array of existent atomizers while still describing important aspects of the atomization physics. Across these classes a limited number of atomization regimes exist which are grouped based on the rate of the atomization processes (disturbance growth and breakdown). Existent classifications are reconsidered to show how they fit into the current construction of five classes (jet, sheet, film, prompt and discrete parcel) and three modes (bulk fluid, mixed and surface). The new framework also clarifies the underlying physics of the atomization process. This process consists of the initiation and growth of a disturbance followed by its breakdown. Several categories of disturbance initiation and disturbance breakdown are described supported by examples from the literature.

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A Fundamental Classification of Atomization Processes (Preprint)

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Abstract

A device-independent framework to classify and describe atomization is developed. This framework divides atomizers into various classes based on the geometry of the liquid prior to breakup. These classes are general enough to encompass a wide array of existent atomizers while still describing important aspects of the atomization physics. Across these classes a limited number of atomization regimes exist which are grouped based on the rate of the atomization processes (disturbance growth and breakdown). Existent classifications are reconsidered to show how they fit into the current construction of five classes (jet, sheet, film, prompt and discrete parcel) and three modes (bulk fluid, mixed and surface). The new framework also clarifies the underlying physics of the atomization process. This process consists of the initiation and growth of a disturbance followed by its breakdown. Several categories of disturbance initiation and disturbance breakdown are described supported by examples from the literature.

Introduction

Atomization plays an important role in processes across many different industries. From the production of powdered metals to the functioning of a gasoline engine, from rocket engines to the delivery of medications and beyond, the breakup of a liquid into droplets is of key importance. Atomization also occurs as a side-effect of some operations, such as droplet production from the bow sheets of ships and the entrainment of liquid in cooling tubes. Due to its commonality throughout a wide range of industries, atomization is an oft-studied phenomenon. Each industry has differing needs and constraints, so it is unsurprising that a vast array of devices has been developed to accomplish and study atomization.

The traditional approach to understanding atomization is to first classify the atomizer by type. Unfortunately, this classification into atomizer types is not based on the mechanisms involved in atomization but on a variety of other criteria such as geometry (e.g., jet in cross flow), relative forces or velocities (e.g., airblast) or usage environment (e.g., diesel). These classifications do little or nothing to elucidate the underlying physics and processes involved with atomization. In fact, some classifications, such as effervescent, may undergo different atomization mechanisms depending on the operating conditions—air-to-liquid ratio in the effervescent case. Similarities between certain atomizer types have been recognized over the years [1-4], but studies generally focus on single types, do not utilize the similarities and works on other types and are rarely used outside of the category about which they were written. These divisions result in an incomplete understanding of atomization mechanisms by unnecessarily and artificially limiting the applicability of much research. As a result, the understanding and development of new atomizer concepts is time consuming and often involves building and testing a large number of prototypes.

A device-free classification of atomization is developed here to more usefully organize the existing atomization literature and identify research needs across applications. A large body of literature, across many traditional classifications, is grouped into a relative handful of fundamental classes. Across these classes a limited number of atomization modes are found; these modes depend on the rate of atomization processes, not on the classes themselves. In other words, they apply to a wide variety of atomizers. From this universal viewpoint, the atomization process itself is seen to result from the basic processes of disturbance formation and growth followed by disturbance breakdown. While the exact mechanisms creating and breaking down the disturbance are a result of relative forces, and to a lesser extent, the atomizer classes, strong similarities are seen across the classes allowing creation mechanisms and breakdown mechanisms to also be divided into a small number of categories.

This paper intends to present this new manner of classification to level which allows readers to perform their own classifications in this system; classification in the new system provides insight into similarities with other systems and a more physics-based description than the traditional divisions. Attempts are made to cover a wide range of common atomizer types either through detailed examples or specific citations. Despite these efforts to be far ranging, this text will focus only on atomizers with fixed nozzles and wall and without imposed body forces. As such, electrohydrodynamic (EHD), ultrasonic and rotary atomizers and the like are not specifically addressed herein. While no difficulties are anticipated in adding these atomizers to the framework, these devices require additional creation and breakdown categories which are specific only to them. They can, therefore, be effectively covered in a later paper without substantially limiting the applicability of the current classification system. Undoubtedly cases will remain which cannot be readily grouped into this framework. No attempt is made to identify or review these here; concentration, instead, is placed on the large number of cases which do fit into the framework.

This paper initially describes the five fundamental atomization classes and three fundamental atomization modes listed in Tables 1 and 2. Following that, a large body of conventional literature is examined in order to show how it can readily be grouped into these few classes and modes. Atomization can, in most cases, be considered to consist of a balance between only two processes—disturbance formation and disturbance breakdown. Further, these two processes may be divided into overarching categories of mechanisms as given in Tables 3 and 4. Conventional literature is examined to show how it fits into these categories. Examples of traditional atomizers and classification are compared with the current framework in tables within the Appendix. Throughout the following discussion many words, especially those found in Tables 1-5, are used in very specific ways; consequently, a glossary is provided in the Appendix for easy reference.

Framework

Atomizers may be classified by the geometry of the liquid at the time of droplet creation. By focusing on classifications relevant to the physics of breakup, we arrive at a set of five different classes. The classes, given in Table 1 and Fig. 1, are jet, sheet, film, prompt and discrete parcel. The first, and simplest, class is the jet. A jet has a single interface in contact with the gas. This interface is usually considered to have a circular cross-section (Fig. 1a), but can generally be any shape provided it may be broadly described by a single characteristic dimension, a "diameter." Now, assume that the cross-section of the jet is elliptical. As the major axis of the ellipse is increased a critical point will be reached where the liquid can only be described, even in a rough sense, by two characteristic dimensions: for the elliptical cross-section these dimensions are the major and minor axis; more traditionally they are the sheet width and thickness. With two distinct dimensions, the liquid is considered to be in the sheet class of atomizers (Fig. 1b), and is considered to have two interfaces which are both in contact with the gas. Sheets can have many configurations, but flat (Fig. 1b) and annular, including conic, (Fig. 1c) are the most common. Note that, as with the elliptical cross-section jet being a limit of the flat sheet case, a circular jet is the limit of the annular sheet case as the inner radius goes to zero. If one side of the sheet is in contact with the wall, then the liquid is in the film class (Figs. 1d & e). As with sheets, films can have multiple configurations such as flat and annular. In these three cases of jet, sheet and film, there is a liquid core in contact with the gas and some feed into that core, ensuring its continued existence. The other two classes differ. In the prompt class, the liquid core is never allowed to form; atomization is instantaneous as soon as the liquid contacts the gas. The discrete parcel class, on the other hand, has no feed into the bulk liquid—the liquid exists separate from the injected liquid in the form of droplets or ligaments. This class of atomization has typically been titled secondary atomization; the first four classes are typically called primary atomization. Primary atomization is the focus of this paper, so elaborations of the discrete parcel class are left for the future. Many of the processes applicable to the other classes apply to parcels as well, and the current framework should present a means for describing discrete parcel breakdown. The Atomization Classes and Modes section is organized based on these classes.

Regardless of class, atomization results from the formation and breakdown of disturbances on the surface of the liquid. Disturbance formation includes the creation, propagation and growth of a wave, ligament, perforation or other disturbance. Disturbance breakdown is the creation of a separated ligament or droplet from the disturbance. Formation and breakdown processes can be grouped into a handful of categories, given in Tables 3 and 4, respectively. Formation categories generally describe the root cause of the disturbance—liquid structures, hydrodynamic instabilities, gas structures, pressure fluctuations, wall effects or particle formation. In the liquid structures category disturbances are formed when turbulent eddies or organized structures in the liquid contact the interface and deform it. A hydrodynamically unstable flow produces waves which grow over time in the hydrodynamic instability category. These waves may be localized three-dimensional disturbances or wider, two-dimensional projections. When vortices in the gas-phase cause an alteration in the interface geometry the formation process falls into the gas structures category. The pressure fluctuations category involves changes in pressure which create pulses of liquid or cavitation and, hence, cause disturbances to form. Particle formation encompasses the production of any discrete object which goes on to interact with the interface; this could be a droplet, a bubble or a solid. Solid particle interaction is not considered here as it is rarely of primary concern in atomizers. Since the focus of this manuscript is droplet formation it is not addressed separately in the particle formation category. Only bubble creation is considered in that subsection. However, both droplet and bubble interaction are discussed from a disturbance breakdown perspective. Wall effects only occur in films and encompass disturbances directly created as a result of the film conforming to the wall or flowing around a projection. Finally, a perforations category is included, in part, because uncertainty regarding their underlying source remains. This final formation category deals with a single type of disturbance whose root cause may be encompassed by other categories. The growth rate of disturbances caused by perforations is quite different from the growth rates of other disturbances, however. Due to the difference in growth rates and uncertainty in root cause it is given its own category here; when the root-causes of perforations are more understood it could be a subcategory of these root-cause-oriented categories. For example, if perforations are found to result from either localized hydrodynamic instabilities or wall effects then both categories would contain a perforation subcategory which would contain information about the growth rate of the perforation. Details and examples of these disturbance formation categories are given in the Disturbance Formation section.

In order for atomization to occur a disturbance must evolve into a discrete parcel, i.e. a separated ligament or droplet. This evolution process requires a finite time and a minimum disturbance height: not all disturbances break down into droplets. Descriptions of disturbance formation are an important part of, but do not fully describe, atomization. Disturbance breakdown is the necessary, second part of the processes. The five categories of disturbance breakdown are instability, stripping, surface, perforation and particle interaction (Table 4). Instability breakdown occurs when the interface essentially contacts itself, another interface or the wall due to its continued growth alone (i.e., tearing or other interface movement is not responsible, only disturbance growth). This type of breakdown is classically seen in the Rayleigh-type breakup of jets and ligaments and is schematically illustrated in Figs. 2a, 4a and 6a. Stripping is one of the most commonly described mechanisms in film atomization. It occurs when lift or drag forces on a disturbance, or part of a disturbance, cause it to separate from the bulk liquid. Surface breakdown is a large category which includes several subcategories as listed in Table 5. In all of these subcategories, a portion of the disturbance is lost while some part of it remains attached to the bulk of the liquid. Stripping may occur on part of a disturbance, so it could be considered a type of surface breakup, but it also may occur on the disturbance as a whole (as in the breakup of a sinusoidal-like wavy sheet). Consequently, stripping is considered to deserve its own, separate category. Surface breakdown is so named because it often occurs from relatively small disturbances when the atomization is the surface mode, as discussed in the next paragraph. Perforation breakdown includes the evolution process which transforms a perforated liquid into droplets. As with the perforations category of disturbance formation, this type of breakdown is not well understood. As the understanding of perforation evolution matures, this category may be absorbed into other breakdown categories or its name may change to be more descriptive of the actual physics involved. Finally, particle interaction deals with the creation of droplets resulting from bubble rupture and droplet collision. As mentioned above, foreign particle collisions are not considered here as they are not generally utilized as a method of atomization. The Disturbance Breakdown section describes each of these categories in more detail.

Since atomization results from the growth and breakdown of disturbances, it may be broken into modes (see Table 2) based on the rate of disturbance growth and the rate at which the disturbance breaks down, i.e. the size the disturbance is able to attain before droplets are produced. If breakdown is rapid compared to growth, then a small droplet is produced from a relatively small disturbance. Long breakdown times compared to growth rates result in large droplets and disturbances. Therefore, it makes sense to divide atomization into a mode where the disturbances and droplets are small compared to the relevant characteristic bulk liquid dimension (jet diameter or sheet width, for example) and one where disturbances and droplets are large in comparison to the bulk liquid. The term surface mode is chosen for the regime resulting in small-scale droplets and bulk fluid mode is picked for the other: the bulk fluid mode generally causes a direct breakup of the intact liquid core, i.e. bulk fluid, while in the surface mode the core is gradually depleted due to the breakdown of many projections on the liquid's surface. Because there are a variety of disturbance creation and breakdown mechanisms and several may be active on the liquid, a third regime occurs when multiple mechanisms produce multiple characteristic scales. For example, perforations in a sheet may produce small droplets and a series of ligaments which then break up into relatively large droplets. This regime generally occurs as a transition between the bulk fluid and surface modes. It will be called the mixed mode. As will be seen from the future discussion, the prompt class of atomizers exists either as a result of very rapid breakdown rates or the failure to form anything resembling a core. If very rapid breakdown occurs, the prompt class is operating at the extreme end of the surface mode. Jets, sheets, films and discrete parcels operate in any of these three regimes. The Atomization Classes and Modes section relates the traditional atomization regimes given in the literature to these three fundamental modes. Atomization modes are discussed prior to disturbance formation and breakdown categories as the discussion of traditional regimes gives many examples which can be utilized in the disturbance categories' discussions. A glossary of the above-discussed terms may be found in the Appendix along with tables of examples.

Atomization Classes and Modes

Jets

The literature on jet atomization is quite extensive. The current text is a basic overview of atomization regimes and by no means a comprehensive review of the subject. Many excellent reviews of jet atomization exist and the reader is referred to Lefebvre's text [5] or the articles of Lin and Reitz or Chigier and Reitz [6, 7] (jets in quiescent atmospheres), Lasheras and Hopfinger [8] (jets in coflow), Faeth [9] (jets in cross-flow) or any of numerous other review articles.

Whether or not the gas phase is moving plays an important role in atomization since it affects the forces on the jet and, consequently, the formation, growth and breakdown of disturbances on its surface. Traditionally, jets are broken into types based on the gas-phase environment—quiescent, coflow and crossflow. (Sheet and film literature make less clear-cut or no distinctions along these lines.) These environmental distinctions are unnecessary in the current framework; however, since current literature uses this segregation it will be employed in the discussion below. A summary is consequently included to simplify the discussion back to the single class of jets. Simplified illustrations of the three generalized regimes appear as Fig. 2; Fig. 3 contains more realistic, but still generalized, sketches based on experimental pictures.

Quiescent Environment

Jets exiting into quiescent environments are traditionally divided into four main regimes. These regimes are titled Rayleigh breakup, first wind-induced or nonaxisymmetric Rayleigh breakup, second wind-induced or wind stress, and prompt atomization [6-8, 10-13]. Chigier and Reitz [6] present very clear photographs of each regime in their paper. There is some slight and occasional variation in this wording, but these four are generally agreed upon.

Both the Rayleigh mode and the first wind-induced mode are characterized by disturbances on the jet surface which are on the order of the jet diameter. These disturbances grow until the column becomes so narrow that the interface meets and a droplet is formed. This droplet is on the same order as the characteristic jet dimension. Figure 2a contains a generalized diagram of this process, and Figs. 3a & b includes experiment-based sketches of both regimes. In certain circumstances small satellite droplets will also be formed. The disturbances on the surface are caused by hydrodynamic instabilities. In the Rayleigh mode the instabilities are purely driven by surface tension forces; in the first wind-induced mode aerodynamic effects are important and enhance disturbance growth and may alter the instabilities. This regime is fairly well understood with investigations into the instabilities going back to Lord Rayleigh [14]. These regimes fall into the bulk fluid mode as the disturbances and droplets are on the order of the jet diameter.

Disturbances and droplets are much smaller than the jet diameter in the second wind-induced regime. In this regime, aerodynamic effects dominate surface tension effects and a large number of small disturbances appear on the surface of the jet. These small disturbances are enhanced due to the relative velocity between the jet and the environment and eventually break up into small droplets. Perturbations may be caused by liquid turbulence [9], hydrodynamic instabilities [15] or the interaction of gas-phase vortices and the interface [16]. Various mechanisms, discussed in the Atomization Mechanisms section, cause these protuberances to break down into droplets. This mode differs from the more columnar mode observed above due to the scale of disturbances and droplets created (see Figs. 2c & 3c) and falls into the surface mode.

In the final regime, prompt atomization, the jet disintegrates immediately upon exiting the nozzle with no observable intact length (Fig. 2d). Reitz and Bracco [17] performed a through analysis of this regime and suggested several possible causes for the liquid's breakup. In the end, however, it seems highly probable that the atomization is not actually instantaneous, but that some intact length exists on which disturbances quickly form, grow and breakdown. As discussed in the introduction to this section, this regime fits into the prompt class, not the jet class, and the surface mode. This class and Reitz and Bracco's [17] work are discussed in more detail below.

Coflowing Gas

Jets with coaxial gas flows share many similarities with jets exiting into quiescent environments. In most cases, a coaxial gas flow increases the relative velocity or momentum flux ratio between the gas and liquid beyond what would typically be seen in the quiescent case. Three main regimes are discussed in the literature with a fourth, prompt atomization, implied but rarely specifically discussed. Unlike the quiescent case, these modes do not seem to have concise names used throughout the literature. Instead they are referred to as Rayleigh-type breakup, breakup via a stretched-sheet mechanism and breakup via fiber-type ligaments [6, 7, 13].

The Rayleigh-type regime is analogous to the same named regime and the first wind-induced regime seen in quiescent atmospheres (Figs. 2a, 3a & 3b). Again, disturbances on the order of the jet diameter are seen, the jet breaks up into droplets on this order and the disturbances are mainly a result of hydrodynamic instabilities. As in the first wind-induced regime, aerodynamic forces play an important part in the final breakup. Again, this fits into the generalized bulk fluid mode—a large (compared with the characteristic dimension) portion of the liquid is separated from the bulk as a result of large-scale disturbances.

The gas flow broadens the jet into a curling sheet which is stretched into a thin membrane bound by thick rims in the breakup via a stretched-sheet mechanism. The thin membrane eventually ruptures into small droplets and the rims break into droplets on the order of the size of the rim. The bulk of the liquid is in these large droplets formed from the rim breakdown either through Rayleigh breakup or due to the flapping of the jet. Figure 2b shows a simplified illustration of this breakup process in the jet in crossflow geometry, and Fig. 3c shows a sketch of the process found in jets in coflow. This process resembles the bag-breakup mode of secondary droplet breakup [4, 6] as well as a breakup regime seen in jets in cross-flow. This regime falls into the mixed mode which is characterized by multiple scales.

The third mode, breakup via fiber-type ligaments, is characterized by the appearance of many small ligaments on the surface of the jet. These small ligaments break down into small droplets. This regime, then, is clearly part of the surface mode with droplets much smaller than the jet diameter produced (Figs. 2c & 3c). It is in many ways equivalent to the second wind-induced regime except that the liquid velocities at which it occurs may be much lower when a coflowing gas is present.

Cross-Flowing Gas

Jets in cross-flow have received a large amount of attention since they are common in air-breathing jet engines as well as numerous other places. The nomenclature for jets in cross-flow is not as universal as that for the other configurations and there are several more modes given. The most common nomenclature equates the jet breakup with secondary breakup of droplets. As a result, the breakup is classified as bag, multimode or bag-shear, and shear [9, 18-20]. An additional regime is analogous to the first wind-induced regime above and is variously called column [9, 20], Rayleigh type [21], arcade [22] or enhanced capillary breakup [18]. Some authors include a turbulent regime [18, 19, 23] and others include a surface/column regime [18].

The bag mode is quite similar to the breakup via a stretched-sheet mechanism of coflowing jets where the jet is stretched into a thin sheet bounded by two rims. The sheet ruptures downstream leading to the breakup of the rims bounding it. Clearly, this is a mixed mode (Figs. 2b & 3d). In the shear mode the jet column deforms and droplets are stripped from its edges as in the shear mode of secondary breakup; ligaments are formed by shear forces at the downstream edge of the deformed jet. This is analogous to the second wind-induced regime or breakup via fiber-type ligaments regime and fits into the surface mode (Figs. 2c & 3c). The multimode regime highlights a complication of atomization touched-on above: the transition from one regime to the next is not instantaneous. A realm of transition exists where main features of both bounding regimes, in this case the bag and shear regime, are present. Due to the multitude of scales, this is a mixed mode, but most easily studied as a mixture of the two bounding regimes.

In the column/Rayleigh/arcade/enhanced capillary breakup mode aerodynamic forces enhance the breakup of the jet into droplets which are on the order of the original jet diameter. Again, large-scale disturbances caused by hydrodynamic instabilities are at the root of the breakup and the process falls into the bulk fluid mode (Fig. 2a). The turbulent regime is characterized by small disturbances on the surface of the jet which are caused by turbulence in the liquid. These disturbances cause the jet to break up into droplets much smaller than the jet diameter; this regime is part of the surface mode and is essentially identical to the second wind-induced regime in terms of the underlying atomization process (Figs. 2c & 3c). Finally, the surface/column regime is a transitional regime where an appreciable amount of the jet breaks up due to one of the surface modes, but a large amount of the original jet remains intact and breaks into large droplets as in the bulk fluid mode. Again, this is a transitional regime, part of the mixed mode and is best studied as a melding of the two extremes. Note that the earlier descriptions have progressed from low to high speeds when giving the traditional regimes, but the discussion here is not in this order. The regimes typically fall in the order of column,

column/surface, bag, multimode and shear. In other words, as above, they progress from a bulk fluid mode to a mixed mode to a surface mode.

Jet Summary

Classical jet regimes have been considered here in the framework of three, generalized modes. The bulk fluid mode is seen to encompass Rayleigh and Rayleigh-like regimes that occur with jets in all three environments. These regimes are variously titled first wind-induced and column as well as Rayleigh-like, but have the same underlying instability-induced disturbance which breaks down due to the growth of an instability causing the entire downstream section of the jet to detach. Jets exiting into flowing environments classically exhibit a bag or stretched sheet breakup mode that results in two droplet sizes, one from a ruptured membrane and one from the breakup of the ligaments bounding the membrane. This atomization falls in the mixed mode. Small-scale disturbances and, hence, the surface mode seems to be the most varied among the different classical jet configurations. This seeming variance occurs because a large number of creation and breakdown mechanisms exist in this mode. In all three jet environments, a liquid-turbulence-induced mechanism resulting in surface breakup is reported and, regardless of the exact mechanism the regimes all progress with the growth and relatively rapid breakdown of disturbances resulting in small droplets. The above discussion also highlights one of the messy complications of atomization regimes and a main reason to consider a mixed mode: the boundaries between the regimes are not hard, but a continuum from one mode to the next with most atomization showing various amounts of more than one classical regime.

The beauty and power of these generalized modes is that they point out similarities and allow an initial understanding and expectation when new atomizers are encountered. This can be illustrated by examining turbulent jets, which are often studied separately from the above literature and regime classifications. From the generalized framework three types of atomization are expected: one in which the entire column breaks up into large droplets, one with multiple scales, probably involving a membrane bounded by rims, and one where a lot of disturbances on the surface break up into small droplets. In Faeth's [9] review of turbulent jet breakup he reports three modes. The first is the bulk fluid mode where the entire column breaks up. The other two are part of the mixed mode and are transitional where a percentage of the column atomizes via small disturbances and the remainder breaks up as a whole. Sallam, Dai and Faeth [3] later report a mode where the entire column breaks up into small droplets (surface mode) and an aerodynamic bag breakup mode where the turbulence causes very large scale oscillations of the jet; at the "corners" of the tortuous jet bag-like breakup (mixed mode) is seen.

Sheets

Jets and sheets are traditionally considered to be dissimilar due to their obvious difference in appearance. And, indeed, the breakup of liquid jets and sheets differ in various ways. Most notably, surface tension is stabilizing in sheets with Weber numbers greater than a critical value, which is dependent on fluid properties and flow conditions [24]; conditions in almost all atomizers have Weber numbers exceeding this critical value. The general breakup processes of jets and sheets are strikingly similar, however, particularly when examined from the viewpoint of the generalized modes introduced above. These similarities suggest strong similarities with film atomization as well, since films and sheets superficially resemble each other more strongly than jets and sheets. One clear example of the ability to compare the three geometries is the study of liquid-turbulence-induced atomization mechanisms where the breakup process has been shown to be similar across the classes [3, 25]. As with the Jet subsection, this subsection is a much abbreviated overview of sheet atomization with a focus on atomization regimes. The reader is directed elsewhere for more in-depth reviews, e.g. Lefebvre's [5] book on atomization or the paper by Sirignano and Mehring [26].

Two different configurations are commonly encountered in sheet atomization: flat and annular (Figs. 1b and 1c). Most of the breakup phenomena are similar [27], but annular sheets have some additional complexities in the ability to impart swirl to either of the gas flows and/or the liquid flow. This swirl can change the evolution of the sheet, particularly the evolution of waves on its surface [28, 29], but the atomization regimes and general mechanisms responsible for droplet formation do not appear to change [30]. Additionally, the curvature of the sheet in the annular geometry can enhance the growth of waves on the sheet's surface [24]. The added complexity of possible pressure differences between the inner and outer gas flows can lead to a unique atomization behavior where the downstream edges of the sheet come together forming an enclosed gas pocket [11]. Under most conditions this bubble necks down at some finite distance from the nozzle and separates a large chunk of the sheet from the bulk. The bubble then undergoes further breakup. Due to the large-scale disturbance and separation of a large section of the sheet, this mode falls into the bulk fluid regime, even though the bubble (atypical parcel geometry) undergoes further breakup into small droplets. In this bubble breakup regime, atomization results from the unbalance in the pressure and surface tension forces.

In addition to surface tension causing the sheet to collapse into a jet, five additional regimes are often cited for flat sheets—prompt, surface, stretched streamwise ligament, cellular and wavy sheet breakup. Stylized illustrations of the regimes are given in Fig. 4, and sketches based on experiments are contained in Fig. 5. As with jet atomization, sheet atomization may be fast enough to be considered prompt [30, 31], where disintegration takes place immediately upon exiting. However, as stated earlier, this falls into a prompt class, not a sheet class. More details on the prompt atomization regime are given at the end of the Atomization Mechanisms section. Sheets possess a surface mode, generally untitled in the literature, where small disturbances exist throughout the surface of the sheet and produce small droplets [11] (Figs. 4d & 5c). Surface perturbations may arise from liquid turbulence or other causes. Sheets also have a bulk fluid mode, called the wavy sheet mode, where hydrodynamic instabilities grow and cause a section of the sheet to separate from the bulk [10, 12, 31]. This section extends over the spanwise dimension of the sheet and further breaks up into droplets following separation (see Figs. 4a, b & 5a). The formed ligament is an example of the discrete parcel class and shows how this class slightly differs from the traditional secondary atomization classification. Since surface tension is generally stabilizing in sheets [24], the instabilities are usually considered a result of the velocity difference between the liquid and gas. The wavy sheet regime is sometimes broken into three subregimes depending on the type of waves present—sinusoidal, dilational or both—but this underlying process is the same with the main differences arising from the exact disturbance growth and breakup details. This regime has garnered the most attention in the sheet atomization literature and is implemented in numerous numerical calculations ([32-34], for example). The final two regimes, cellular and stretched-streamwise ligament, involve the formation of cell-like structures bounded by thicker rims [11, 12, 35, 36]. Due to sheet flapping and aerodynamic effects the membranes of these cells may be stretched as in the bag-breakup of jets. Indeed, the stretched-streamwise ligament regime strongly resembles a series of bag-breakup events where a number of cell membranes rupture leaving a network of small ligaments which break up into droplets (see Figs. 4c & 5b). Clearly, as in bag-breakup, this is a mixed mode type of atomization. Similar cellular structures may occur at lower gas velocities when streamwise ligaments are less obvious or nonexistent; in that situation, the regime is generally titled perforated [37]; again, though, the holes in the sheet grow until they produce a random network of ligaments and some small droplets. In these regimes, the bulk of the discrete parcel volume comes from the ligaments, but membrane rupture or the collision of the rims produced by hole growth produce a series of smaller droplets. The last regime, the cellular regime, may be a transitional regime or may be a special case of the wavy sheet regime where a cellular structure exists. This regime is characterized by a cell-like structure with much less pronounced streamwise ligaments than the stretched-streamwise ligament regime. When the cell membranes rupture they may again be bag-like, but they produce a single, spanwise ligament instead of a network of ligaments [12, 36]. Both the spanwise disturbances which eventually form the ligament and streamwise disturbances responsible for the cells are generally considered to result from hydrodynamic instabilities. This regime is in the mixed mode, but is also a transitional regime between the pure wavy sheet and the stretched-streamwise ligament regimes. In order of increasing velocity, the bulk fluid (wavy sheet) mode is again followed by the mixed (stretched-streamwise ligament) mode which is followed by the surface mode.

The regime names for annular sheets differ slightly, but the behavior and appearance are very similar to flat sheets. In the Rayleigh mode the sheet collapses to a jet and breaks up in the bulk fluid mode. The annular sheet possesses other bulk fluid mode subregimes including the bubble mode discussed earlier and a wave or Kelvin-Helmholtz mode [11, 30] which involves the growth of instability waves and the separation of an annular ligament from the sheet. A regime involving cellular structures and ligaments [30], a mixed mode, is seen as well as a surface mode with small disturbances projected from the sheet's surface [11, 30].

As with jets, breakup occurs in three main modes. Large-scale disturbances (instabilities or pressure-surface tension effects) cause the separation of a large, in this case spanwise or annular, section of the liquid; a series of membranes bounded by thick rims rupture leading to small droplets and a series of ligaments which produce larger droplets; or numerous small-scale disturbances exist throughout the interface causing small droplets to be created. Here it also becomes more obvious that the three generalized modes share a common evolution. A disturbance—wave, ligament or hole—is created on the surface. This disturbance grows and may be deformed or changed by the forces acting on it. Eventually the disturbance breaks down into parcels. The Atomization Mechanisms section focuses on the causes of disturbances and the methods of their breakdown.

Films

Much of the literature regarding film flows is focused on water waves in oceans or spillways, where atomization is not the main emphasis. Another large body of literature exists on heat-exchanger pipes where the focus is predicting film depths and/or heat transfer; these works are often concerned about atomization. Research on heat-exchangers is centered on the entrainment rate of the liquid, not on the mechanisms by which the liquid becomes entrained.

The literature that does address atomization mechanisms in films considers only a surface mode where small disturbances on the film surface evolve into droplets ([38-40], for example). Given the earlier discussions, however, a bulk fluid mode would also be anticipated. In this mode a spanwise disturbance would grow until a large, spanwise ligament was separated from the film. In some instances this ligament might be air borne, but it is more likely that it would occur when the disturbance reached a size where part of the interface contacted the wall. In this case, the ligament would be bounded by the wall and less likely to produce droplets than a free ligament due to the additional solid-liquid-gas surface tension. If a bulk fluid mode and a surface mode exist, then there will be a transitional regime in the mixed mode with multiple scales. A perforation-controlled breakup might also occur with the film rupturing into a series of ligaments or, since likely to be wall-bounded, rivulets. Despite holes occurring more commonly in films than sheets due to wall unevenness and spontaneous dewetting [41, 42], the extra surface tension created by the wall contact would slow any breakdown of perforations into droplets thus creating no or larger droplets than in the jet or sheet bag-breakup case. Rivulet breakdown would also differ from ligament breakdown and might not produce droplets. A mixed mode based on perforations is therefore possible, but unlikely in films; the less wetting a liquid-wall combination is, the more likely this mode would occur. One final regime implied by the literature is a prompt regime. As stated above, this is really a specific class in and of itself, not a regime. The film configuration illustrates this nicely: if atomization is truly prompt then no intact, wall-bound liquid exists. In other words, if a film atomizer and sheet atomizer were both identical except for the existence of a wall in the former, then they would behave identically as the breakdown time went to zero and no intact liquid existed. Simplified illustrations of the suspected appearance of these modes are given in Fig. 6. One last note on the similarities of sheets and films is the existence of multiple configurations such as flat and annular. As with sheets, the configuration is not expected to affect the underlying atomization process, only the specific details of the forces involved.

<u>Prompt</u>

The prompt class of atomization and its potential causes are briefly considered here for completeness. This class may not truly exist for the atomizers considered here, being more applicable to so-called drop-on-demand applications of ultrasonic and other moving-wall atomizers. The prompt class is considered to produce immediate disintegration upon the liquid's exit from an atomizer (Fig. 1f), but Reitz and Bracco [17] note the possibility that there is still some (undetectably small) intact length of the jet and that atomization, therefore, is not truly instantaneous. This definition fits within the current framework if the prompt class is considered to occur when the breakdown time for a disturbance tends to zero, i.e. breakdown becomes infinitely fast. Clearly, the assertion of an undetectably small intact length is not verifiable, but would mean that the following section on disturbance formation and breakdown categories would equally apply to the traditional prompt regime. Recent results [43, 44] suggest that the common single orifice atomizer does indeed have a small, intact length. However, a review of other possibilities for breakup in the prompt class is given here as other atomizers may exist without this intact length. The breakup of liquids in this class which would form jets under slower breakup has been variously attributed to cavitation, liquid turbulence, velocity profile relaxation, acceleration in the boundary layers, pressure fluctuations and aerodynamic effects, although experimental findings concluded that no single mechanism can explain the entire regime [17]. A few potential arguments for additional mechanisms can be gathered from the literature where slower atomization would result in sheets. Drop-on-demand literature suggests some types of prompt atomization result form changes in liquid velocity; this possibility is not described in detail here as it generally results from wall movement [45].

Velocity profile relaxation causes atomization due to the perpendicular velocities which may be already present in the liquid or may be caused by the liquid's change from confinement to free. Similarly, boundary layer relaxation/acceleration causes disintegration due to the changes in tangential stress at the interface and instabilities associated with the sudden change in boundary conditions. Studies show that the boundary layer profile affects instabilities on the surface of jets, sheets and films [46, 47]; this effect could clearly be important if there is any intact liquid where the disturbance creation would be due to hydrodynamic instabilities. Neither of these profile mechanisms has been proven, however.

Cavitation, liquid turbulence, pressure fluctuations and aerodynamics effects are known to have an effect on intact lengths of jets, sheets and films and will be dealt with in the next section. For aerodynamic effects to be important a short intact length of fluid must be present. Cavitation causes pressure disruptions that may increase turbulence and help to disintegrate the liquid. Turbulent flow contains a radial component which may cause atomization. Ghafourian et al. [10] give more information about the effect of pressure fluctuations on prompt atomization. Again, in Reitz and Bracco's [17] study of jet atomization, no single one of these were found to be the cause of all atomization behavior, but cavitation and aerodynamic effects help to explain a large part of their findings. The conclusions in that work and later works [43, 44] strongly imply that some intact liquid exists at the exit meaning the traditional prompt regime atomizes at the extreme end of the surface mode.

Some additional, although less detailed, explanations are suggested in literature studying sheet breakup. Work by Khavkin [48, 49] relates the droplet size produced in the prompt class back to the Kolmogorov length scale for turbulence. Khavkin [48, 49] explains his idea through a comparison with the breakdown of turbulent structures where intensive mixing inside the atomizer is equivalent to turbulent diffusion with particles changing their size and location instead of vortices. Particles divide until they reach a stable size determined by viscosity, i.e. the

Kolmogorov length scale. A theoretical description of resultant droplet sizes is formulated, but exact details on the formation of the particles are not given [48, 49]. His studies involve the behavior of pressure swirl atomizers where contact between the two phases may occur prior to the exit; in other words, atomization may not be prompt but instead may occur from the film prior to the liquid exiting the injector. Indeed, recent studies [50-52] observed a large amount of atomization occurring within a similar atomizer in a location where the fluid is a film. This internal breakup mode means there is little or no intact sheet at the exit. Despite appearances, however, this breakup is not truly in the prompt class because film atomization occurs prior to the injector exit and should not be discounted.

Unfortunately, due to the difficulty in studying this class, the preceding list of potential mechanisms is likely not exhaustive but instead a sampling of the commonly discussed possibilities. Taken as a whole, however, the literature suggests that few atomizers operate in this class, but instead have some small but finite intact length on which disturbances are rapidly created and broken down into droplets. In this case, the prompt class then occurs as these time scales become infinitesimally small.

Additional Examples

While many atomizer types are considered in the above review, a few additional classes of atomizers are discussed here to illustrate how they fit into the generalized framework. Brief overviews of the classical diesel, airblast and pressure-swirl atomizers are given. More in-depth examinations of effervescent and impinging atomizers with traditional regime notations follow. Impinging atomizers are mainly discussed from the viewpoint of two impinging jets, but the results and, indeed, much of the overview, applies equally to a single jet hitting a splash plate. Strong parallels should also be recognized to jets impacting wall.

As mentioned in the introduction, traditional classifications often do not capture the physics involved in the breakup of the liquid. These classifications may instead be used to describe specific operating conditions or the manner in which the bulk liquid is delivered (hereafter called upstream conditions) or both. Three common examples are considered here—airblast, pressure-swirl and diesel atomizers. The title airblast atomizer is used primarily to describe operating conditions. In particular, this type of atomizer has a high speed gas which strongly contributes to the atomization. Airblast atomizers have a multitude of geometries and subtypes. Two main subtypes highlight the focus on operating conditions over geometry in this classification—prefilming and nonprefilming. Some or all of the atomization occurs from a wall-bounded liquid (film) in prefilming airblast atomizers. While nonprefilming airblast atomizers are generally sheets with high velocity gas flows on both sides. This classification recognizes, to some extent, the independence of atomization modes from the geometry class, but generally does not include or consider the similarities with jets in high-speed coflows. Pressure-swirl atomizers describe the upstream geometry prior to atomization. In this type of atomizer, a swirling annular sheet is formed following the tangential injection of liquid into a nozzle. The history of the liquid prior to forming a sheet and undergoing atomization may be important in determining the type and growth of disturbances, but it needlessly isolates this type of atomizer from other sheet-forming atomizers with similar behavior. Finally, the term diesel atomizer is used to describe both upstream and operating conditions. The title is generally applied to describe a multihole injector operating at elevated pressures and often implies that the liquid feed is pulsed. Despite differences in upstream geometry from other systems, many diesel injectors still produce jets and fall into the jet class. This classification may be somewhat complicated, however, in that this descriptor may be applied to a system, not just the injector. In the system, the spray may undergo wall impingement as either droplets or the jet hits the piston. Impingement is considered below and wall-bounded atomization is considered in the Films subsection. Lefebvre's book [5] gives a good overview of a multitude of traditional atomizer types. (Some examples of the class and mode of traditional atomizer types are given in the Appendix.)

Four atomization regimes for impinging jets are reported in the literature—collapse to single jet, rim atomization, periodic and fully developed [10, 53, 54]. At low jet velocities the collision initially forms a sheet but this sheet subsequently collapses into a jet [54]. Any atomization occurs from this jet, so has been covered above. Because this occurs at low velocities a bulk fluid mode would be expected from this jet. The three remaining regimes occur at higher jet velocities and atomization occurs from a sheet. The rim atomization regime is characterized by either periodic or random shedding from the edge of the sheet [53, 54]. It is unclear from the literature if the sheet has thinned substantially at the periphery and the thin sheet undergoes a series of perforations which create very small droplets (mixed mode) or if these ligaments are formed by other mechanisms, making them localized surface disturbances (putting the regime in the surface mode). The periodic regime occurs when some turbulent jets collide; this regime is typified by the shedding of regularly circumferentially spaced droplets cast off from the edge of the sheet [10, 53, 54]. According to the description and diagrams given by Anderson et al. [54] and the pictures given by Jung et al. [53] this regime corresponds to the bulk fluid mode where large ligaments are formed. The last regime, at the highest jet velocities tested, is considered to be the fully developed regime where catastrophic breakup occurs; in this regime periodic waves of droplets are shed from the point of impingement and no sheet is evident [53, 54]. In terms of impinging jets, this constitutes a prompt class: droplets are formed at the earliest time possible with no intact bulk liquid; earlier atomization would take place from the jets before they collided and there would be no impingement. Again, the above description is a drastic abridgement of this subject; for further reading the review article of Anderson et al. [54] is recommended. Two similar configurations exist in the classic literature, a splash plate and jet impingement on a wall. In a splash plate geometry a jet impacts a disk of nearly the same diameter as the jet and spreads to form a sheet (Fig. 8). This configuration is in between that of impinging jets and a jet impacting a wall. As shown from the two-jet discussion, these other impinging configurations can be covered in the jet, sheet and film classes. Atomization from splash plates is reviewed in two articles by Clanet and Villermaux [55, 56].

In effervescent atomizers gas is injected into the liquid at a low relative velocity in order to form a bubbly two-phase flow [57]. This two-phase flow has a much lower sound speed than either the gas or liquid alone, thus the flow in the nozzle chokes at much lower speeds. Choking creates a large pressure drop at the nozzle exit. The atomization in effervescent atomizers relies on this pressure drop [57]. Depending on the gas-to-liquid flow rate the flow in the nozzle may be bubbly, slug or annular (Fig. 7). On exiting the nozzle, the air (either the bubbles, slug or the inner column) experiences a sudden pressure drop causing it to expand rapidly [57]. This rapid expansion causes bubbles or slugs to thin the surrounding liquid which breaks down into fine droplets; the annular liquid is fragmented into ligaments by this expansion [57]. Flash atomizers rely on this same mechanism with bubbles produced by boiling or cavitation instead of through injected air [58-60]. For the purposes of classification, internal flash atomizers, those most commonly used [59, 60], are identical to effervescent atomizers. Within this discussion the liquid is assumed to be in the jet class if no gas is present. Due to the repeated expansion events, thin films, perforations and ligament networks may be created (mixed mode); this is most likely if the gas-to-liquid ratio puts the liquid into the annular sheet class. If holes do not appear and produce a series of ligaments, but instead repeated atomization events due to bubble rupture occur on the liquid surface then the atomization would be in the surface mode and the liquid in the jet class; while this situation is possible, it does not appear to be reported in the effervescent literature and would only be expected at low gas-to-liquid ratios where insufficient air exists to fully fragment the liquid. Surface atomization may occur in the external mode of flash atomization; however, this mode is rarely used as it is difficult to control [59]. At extreme ratios, only a wall-bounded film exists in the atomizer nozzle; this film likely breaks up into droplets via a surface mode. Finally, if the bubbles immediately shatter the liquid into droplets with no intact film present then the atomizer is operating as part of the prompt class. With effervescent atomizers the classes and modes are the same as those already seen, but the determining factor is strongly tied to the amount of gas present instead of depending on the upstream geometry or any velocity. For further review of effervescent atomization the reader is referred to the article by Sovani et al. [57]; a review of flash atomization can be found in the recent article by Sher et al. [60].

There are other atomizers that operate over more than one class depending on particular operating parameters. For example, pressure swirl atomizers generally produce annular sheets, but may operate as jets at very low liquid flow rates. Also, as noted above, some types of airblast atomizers may move between the sheet and film classes as the gas velocity is increased. This changeover is particularly reflected in the literature describing swirl coaxial and gas-centered swirl-coaxial atomizers [51, 61, 62]. Another example of a class-changing atomizer is rotary (or centrifugal) atomizers. The class of a rotary atomizer depends largely on the rotational velocity of the substrate: the class moves from film to jet to sheet as the rotational velocity increases. These class changing behaviors highlight a strength of the device-independent classification: more can be learned about pressure swirl atomizers operating at very low flow rates (in a jet class) from comparisons with other jet class atomizers, such as single orifice injectors, than from comparisons with pressure swirl atomizers operating at higher flow rates in a sheet class.

Disturbance Formation

Disturbances may take on various appearances including waves, ligaments, bubbles and perforations. Throughout this section specific nomenclature is used to denote different disturbance types; these types are unnecessary for describing the atomization physics, but they help to clarify the examples given. Here ligaments are liquid projections whose lengths exceed their widths while waves are projections whose width is greater. Waves may occur over the entire surface as seen in the bulk fluid mode, or they may be localized three-dimensional structures as in some surface mode atomization. Bubbles are pockets of gas within the liquid; perforations are breaks or holes in the liquid. The listing of disturbance formation categories is given in Table 3. This section also highlights the gaps and limitations in the current knowledge in an attempt to motivate and focus future research.

Liquid Structures

Liquid structures take two main forms—coherent, ordered structures like recirculation zones or helical vortices [63, 64] and turbulent eddies [2, 18, 65]. Liquid turbulence is one of the commonly considered disturbance-creation mechanisms in jet, sheet, film and prompt classes. Disturbance creation via coherent liquid structures has received substantially less attention, particularly in terms of atomization, being mostly studied in oceanic flows, particularly in the case of wall-interactions [63, 66, 67] . Coherent structures may act directly by forming a protuberance or indirectly through changing the nature of the flow (e.g., velocity profile, stability and turbulence changes) [64]. The direct formation of a wave via coherent structures interacting with a wall is the most likely scenario for direct formation and is addressed in the wall effects subsection. No other types of direct formation are discussed here due to the lack of literature presenting any other examples. Instead, this section focuses on disturbance formation via liquid turbulence. Two different disturbance formation mechanisms have been suggested. In the most common one, turbulent eddies interact with the interface between the liquid and gas causing ligaments to form. In the second, the transition to liquid turbulence causes solitary waves to form in accelerating film flows.

Sarpkaya and Merrill [65] give an in-depth description of turbulent eddy dynamics in flat films while Faeth and coworkers present a simplified, quantitative model of ligament formation [2, 68] and Mayer [69] gives detailed pictures from numerical simulations of eddies interacting with an interface. The theories have been favorably compared with several experiments; in fact, atomization does not differ appreciably between jets, annular sheets and (exterior) annular films atomizing in the surface mode [1, 25]. Despite these successes, some complications have also been discovered. For example, experiments by Sarpkaya and Merrill [65] on flat films found that any roughness on the surface of the wall disturbs the entire film and has a marked effect on ligament formation and droplet production. Their findings are based on roughness heights of 0.13 mm at a minimum in films at least 5.4 mm in depth and indicate that roughness must be accounted for to achieve accurate quantitative descriptions. Also, these experiments have, in general, neglected any aerodynamic effects which may serve to either enhance ligament growth and breakdown (through stripping) or decrease atomization by causing the ligaments to topple before breakdown can be achieved [65].

The second mechanism of solitary wave initiation at the transition to turbulence is put forward in recent work by Lioumbas et al. [70]. Solitary waves are defined as waves with large amplitudes and relatively long wavelengths. Their findings are for inclined, stratified pipe flows with and without parallel gas flow, but the findings are similar to those for flat, free falling films. The intermittent way in which flow transitions from laminar to turbulent is suggested as a reason for the intermittency of the solitary waves, which are separated by relatively large stretches of smooth, flat film [70]. Artificially induced solitary waves have been shown to break down into droplets in otherwise nonatomizing flows [40]. Due to the relative newness of this theory, no additional details and no quantitative description have been found in the literature.

Hydrodynamic Instabilities

The most commonly considered disturbance creation mechanism is probably hydrodynamic instabilities. Many different types of instabilities exist; those most commonly considered in atomization works are Rayleigh, Kelvin-Helmholtz and Tollmein-Schlicting. These unstable flows lead to the creation of surface waves. The waves may be localized or occur throughout the interface. They may cause a large section of the bulk liquid to separate (bulk fluid mode) or, at other operating conditions, cause only a small fraction of the waves to break down (surface mode). Due to the large body of work on this subject, the description given below is greatly abridged. The reader is referred to the many references in this discussion for greater detail.

The type of instability present depends on the relative values of forces acting on the liquid. Commonly considered instability driving forces include surface-tension, aerodynamic shear, air turbulence and/or viscous stratification. A large and robust body of work on surface-tension-driven instabilities, particularly the Rayleigh instability, of jets exists ([14, 46], for example). While generally not existent in sheets and films as a whole, the Rayleigh mechanism is responsible for the breakdown of ligaments on sheets and films for many operating conditions (see the instability breakdown category below). Kelvin-Helmholtz instabilities receive the most interest in sheet atomization; Kelvin-Helmholtz and Tollmein-Schlichting instabilities are most often emphasized in film analyses [71, 72]. Kelvin-Helmholtz instabilities are driven by aerodynamic shear; Tollmein-Schlichting instabilities arise due to the effects of gas-phase turbulence. A thorough theoretical investigation by Boomkamp and Miesen [73] examines several instability sources in depth and classifies instabilities in infinitely deep films. It is interesting to note, although not directly relevant to the current work, that Boomkamp and Miesen [73] conclude that Kelvin-Helmholtz waves per se do not exist in viscous film flows—the introduction of "viscosity effects, however small, into the stability problem rules out the possibility of the essentially inviscid Kelvin-Helmholtz instability" [73]. For further reading on the subject of instability theory the notable text of Drazin and Reid [74] is recommended in addition to the seminal works listed below.

Due to the large body of work in sheets and films and complications that arise in these geometries, the following look at current shortfalls and unresolved issues focuses on the sheet and film classes. Theoretical investigations into the aerodynamic instabilities of flat sheets began more than fifty years ago; seminal works in this geometry include those by Squire [75] , York et al. [76], Hagerty and Shea [33], Dombrowski and Johns [77] and Li and Tankin [78], among others. Film instability analysis has its own set of seminal works ([79-82], for example). Most of these seminal works and most current work focuses on temporal instabilities, where the growth rate is considered a function of time [83]. There is, however, a body of literature examining spatial instabilities, where the growth rate is a function of distance [83]; a limited amount of work focuses on both separately ([26], for example). Few studies address the full temperospatial stability due to the complexity of the resulting equations [15, 26], and continued debate exists on whether the temporal or spatial viewpoint is more appropriate [12, 15, 83]. A further complication to this debate is recent numerical studies that suggest the short-term temporal growth is important even for waves which are stable at long times [84-86]; this line of investigation shows promise because it has predicted specific three dimensional structures, streamwise ligaments [86], that classic instability analyses have had difficulties predicting [87]. An additional debate arises from the use of linearized equations to describe the instabilities. The vast majority of analyses are linear in nature due to the extreme complexity of the nonlinear formulations. Questions have been raised about the applicability of the linear theories; these must assume that disturbances are small whereas in the bulk fluid mode the disturbances are large [75, 76, 88]. Also, nonlinearities are, in part, responsible for the size distributions of droplets in a spray [89]. Clearly, the subject of hydrodynamic instability and instability growth on sheets is a complex and active topic worthy of its own review article; definitive conclusions on wave sizes, causes and growth rates are not yet available for the range of conditions and geometries at which atomization occurs.

To test predictions made from hydrodynamic-instability theory wavelengths can be measured from photographs or from air speed fluctuations near the liquid [31] and compared to predictions. Even with good experimental measurements, though, assessment of theoretical agreement is complicated because it is difficult to make exact predictions due to the limited knowledge of the flow parameters in the nozzle and after the liquid exits; theories may require the pressure drop across the nozzle [75], the shear layer thickness [8] or other parameters not easily measured or predicted. Despite these difficulties, experimental comparisons have been favorable for jets, sheets and films [8, 16, 90-92].

Hydrodynamic-instability theories predict a most unstable wavelength as the one with the fastest (shortest) growth rate and suggest that this wavelength dominates and, hence, the droplet size is proportional to it [76]. This assumption has been successfully used in the generation of empirical correlations [90]. Despite successful comparisons, an additional complication was uncovered in a recent study by Boeck et al. [93]. Their numerical work showed that different droplet diameters (still in the range expected for the Instability regime) could be generated from the same disturbances, including the same wavelength of the disturbance [93]. These findings suggest that not only wavelength, but other properties of the instability are important, for example amplitude and/or evolution time. This highlights an important point that must not be overlooked in stability analysis: the existence of an instability does not guarantee that atomization will occur. A time scale is involved for the growth of the instability; other mechanisms may break up the liquid before the instability grows sufficiently to itself break down. Finally, even a thorough description of instability formation and growth is not an atomization mechanism—a description of how the droplets form from these instabilities is also needed.

Gas Structures

Structures in the gas phase have the ability to displace the surface of the liquid phase provided they posses enough energy to overcome the energy of the liquid [6, 35, 51, 94, 95]. One representation of this disturbance creation mechanism is given in Fig. 9. These structures may be created due to flow separation or they may be a result of gas-phase turbulence. In addition to the direct effects outlined above, eddies can also have more indirect effects such as altering the hydrodynamic instabilities of the system. Compared to liquid structures and hydrodynamic instabilities, little atomization literature exists in which direct gas-phase interactions with the coherent liquid are considered. Most of the literature that does exist involves jets in coflowing or cross-flowing environments ([7, 12], for example). Perhaps the lack of literature is influenced by findings that aerodynamic effects on jets in quiescent environments can generally be neglected, particularly if the liquid-to-gas density ratio is above 500 [2, 68]. Sheets and films, however, are more susceptible to aerodynamic effects than jets.

Investigations of the effects of gas turbulence generally focus on the formation and growth of waves, particularly through the introduction of hydrodynamically unstable flow conditions or by increasing the growth rate of waves [16, 73, 79, 92, 96, 97]. Hydrodynamic instabilities have been addressed in the preceding section and, even if altered by gas-phase turbulence, are considered to be a different category of disturbance formation. A few additional notes and references are given here, however. Jurman and McCready [16] suggest that air turbulence helps cause distortions and waves on the liquid surface without giving a specific mechanism and Park et al. [92] suggest air turbulence is the source of initial perturbations which trigger hydrodynamic instabilities. Also, any surface disturbances can be further enhanced by the turbulent flow of air over them leading to disturbance growth and eventual droplet production [96, 97]. Growth may be additionally enhanced due to the nonparallel orientation of some of the velocity fluctuations [16].

Separated flow at the lip segregating the gas and liquid may force flapping of a sheet (behavior like in Fig. 4b, but somewhat more chaotic may result). Lozano et al. [35] and Lopez-Pages et al. [95] experimentally studied this effect. They found the periodically shed vortices indeed force the flapping. Lopez-Pages et al. [95] found that vorticity can be created purely from the contact of the flowing gas and liquid, i.e. even with an infinitely thin separating wall vorticity is still created in the gas. The flapping created by this vorticity is actually larger with an infinitely thin wall than in the case of a finite wall. Park et al. [92], however, found that stable recirculation zones behind segregating walls actually helped to stabilize a sheet, acting as disturbance dampers. A stationary vortex next to a film might not have the same effect, though, as it could essentially constrict and accelerate the flow passing under it. Additionally, a thicker area of film could be created adjacent to the vortex due to the constriction. The vortex would also change the gas flow downstream of itself leading to different aerodynamic forces. All of these would affect the subsequent behavior of the liquid possibly indirectly causing disturbances or their growth.

As illustrated in Fig. 9, it is possible that vortices in the gas act in ways similar to liquid eddies, contacting the liquid-gas interface and causing deformations. To accomplish this deformation the gas structures must be sufficiently energetic. The example illustrated in Fig. 9 has a clockwise-rotating gas-phase vortex in the main flow. Here the gas is dense and the surface tension is small, so that the gas structure has a lot of energy and the interface has little energy to overcome. The vortex forces the film to thin in the downstream direction and drags fluid up along its upstream edge causing a wave or ligament to form. This mechanism may explain findings in numerical, two-phase film-flow simulations of "large perturbations of the gas-liquid interface with a wavelength similar in size to the scale of the large, energy containing eddies" [50]. No definitive evidence of this mechanism has yet been reported, but the numerical results of Boeck et al. [93] show liquid behavior consistent with such a mechanism, particularly their results where the liquid and gas are the same fluid (no surface tension). In a similar mechanism, studies of solid spheres rotating near, but not touching, interfaces show that the motion of the sphere can deform the interface producing ligaments [98, 99]; sufficiently dense or energetic eddies could produce similar results as could liquid structures.

Pressure Fluctuations and Cavitation

Pressure fluctuations are often caused by changes in the environment outside of the injector, e.g. feedback from combustion instabilities [100]. These environmental fluctuations may even be driven by the atomization process, creating a feedback loop that is very difficult to model. Pressure fluctuations impact atomization mainly by causing changes to the supply rate/velocity of the liquid and gas [100] which change the forces at the interface and can produce "pulses" of liquid. These fluctuations can also be caused by the movement of a wall or piezoelectric element in the liquid plenum or the production of a short-lived, stationary vapor bubble as in inkjet drop-on-dement techniques [45]. Other effects may be present, however, such as the impact waves observed on impinging jets. Cavitation is another pressure fluctuation driver that occurs without any interaction from the environment beyond the nozzle. Also, Adzic et al. [11], among others [27], detail another self-contained pressure-driven process, a "bubble mode", which causes atomization in annular sheets and is reviewed in the Sheets subsection above. Because it is often an important driver for pressure fluctuations, cavitation is reviewed first.

Under certain conditions cavitation can occur within the nozzle or at its exit [58, 101-103]. It occurs in ultrasonic atomization [104], some flash atomizers [58, 59] and is often discussed in engine fuel-feed systems, but several studies have also been done for the basic jet configuration. Cavitation generally occurs at the transition into the nozzle, but can occur at sharp corners in other areas of the injector [102]. Liquids cannot flow around sharp corners, so flow separation and strong streamline curvature results; this strong curvature generates a large pressure gradient along the flow with a low static pressure near the corner. If the pressure drops to the liquid's vapor pressure bubbles/pockets of vapor are formed. This formation of vapor bubbles is called cavitation. Cavitation generally causes disturbances indirectly, most notably by making the flow less steady and increasing the turbulence [105] (see Liquid Structures or Gas Structure subsections). The presence of bubbles in the nozzle reduces the discharge area, causing an increase in the liquid velocity. Unsteady cavitation, either due to bubble collapse or changes in the size of the vapor pocket, causes pressure waves to be sent through the liquid and affects mass flow rates [102, 103]. The consequences of mass flow fluctuations are discussed in the next paragraph. In instances where the cavitation pockets have reached the exit plane a roughened interface has been observed immediately after the liquid exits the nozzle [103]. It is unclear if this roughness is due to an increase in liquid turbulence caused by the cavitation, a result of the greater time the liquid is in contact with the gas or due to some other interaction between the vapor and the liquid—the exact cause of the surface disturbances are unclear but are clearly effected by the cavitation [103, 105]. Cavitation has also been considered as a means of introducing bubbles into a liquid [64, 106] (see Particle Formation section below).

Pressure fluctuations can cause an uneven feed velocity/mass flow for the fuel or gas. If these mass-flow changes are large enough, they can create a change in liquid thickness, e.g. a “bulge” of liquid following a dip in gas pressure. These bulges would likely appear as singular waves with relatively undisturbed interfaces preceding and following them. Experimental studies have shown that pulses of liquid in an annular film configuration can lead to atomization of an otherwise nonatomizing flow [40]. Additionally, changes in fuel and gas velocity alter many of the fundamental characteristics of the flow. These changes alter the subsequent liquid behavior [100] and must be considered even though the disturbance formation may fall into a different category.

In the case of impinging jets, pressure fluctuations (and/or variations in feed velocity) in the jets may lead to impact waves. These waves, instead of waves produced by hydrodynamic instabilities, may be responsible for atomization [53, 54]. The waves are generated by pressure or momentum fluxes in either or both jets; they may be present in a film configuration if the film is formed by a jet impinging on a wall, and they can also appear in the splash plate setup. These fluctuations may be generated inside the nozzle producing the original jet, by the instabilities of the jets prior to impact, due to cavitation in the jet nozzles or due to turbulence within the jet [54]. The velocity profile of the jet also affects impact waves. When the jets are laminar, the boundary layer helps to damp the waves, but the flat profile of turbulent jets does not contribute to damping the waves [53]; consequently, impact waves are more prevalent in the impingement of turbulent jets. Predictions based on theories of impact waves compare favorably with experimental results for the collision of two jets, especially when comparing the differences in the impingement of laminar and turbulent jets [54]. Available literature on atomizers that utilize jets impinging with walls do not report these impact waves, however [91].

Another effect of pressure fluctuations is found for annular sheets and was briefly outlined earlier. The experimental work of Adzic et al. [11], for example, describes several different subregimes in what is here termed the Instability regime (their Kelvin-Helmholtz regime). These subregimes are driven by pressure changes in the interior hollow of the sheet [11]. At low inner-air velocities the sheet forms a hollow bulb shape. The cylindrical sheet comes together at the downstream end creating a closed shape; the interior air is trapped and the additional air fed to the system increases the pressure inside this “bubble”. Eventually the pressure and surface tension forces cause the upstream inlet of the bubble to neck down and seal, often separating a large section of liquid from the upstream mass of the sheet. Liquid instabilities further downstream cause the bubbles to burst. If both inner and outer gas flows are present, the bubble can be quite distorted and, consequently, burst before it is closed [11]. While this bubble-forming behavior cannot directly occur in film flow, an imperfect comparison can be made with flows that change from slug (or near slug) flow to annular flow, where gas flow may be constricted downstream leading to a cyclic buildup of pressure. It is, therefore, worth noting that in sheets, and potentially in films, fluctuations in air pressure may be important, even if they do not affect the liquid feed.

<u>Wall Effects</u>

Changes in the wall bounding a film can lead to the formation of disturbances. Clearly, this category is not important in jets or sheets as they do not have bounding walls. There are two types of effects created by walls: enhancing disturbance creation via other categories, such as roughened walls increasing liquid turbulence, or directly creating a disturbance as a result of wall geometry. Wall geometry may be an isolated bump, a regular repeated pattern such as a sinusoidal profile or an angle causing the film to become thinner or thicker. The size of a defect or projection compared to the film depth plays an important role in the type and size of the disturbance formed.

Small defects can lead to spontaneous dewetting where a perforation is formed [41, 42]; this effect is discussed in the Perforations section. A submerged bump can cause standing waves or changes in the wave spectrum and energy [67]. Repeated small projections (roughness) can change the turbulence characteristics of the film indirectly causing disturbances. Studies by Sarpkaya and Merrill [65] showed the effect of roughness in producing disturbances through increased turbulence. Periodic walls with small to moderate amplitudes may cause a variety of changes in the interface profile. Gravity-driven films flowing over periodic walls exhibit pooling in low spots, hydraulic jumps, surface roll waves and three-dimensional fingering patterns at various operating conditions [107] similar behavior could be expected in other film flows. If the film is deep enough compared to the amplitude of the perforations then the corrugated surface acts like a roughened surface and its affect on disturbance creation is through the modification of liquid turbulence [108].

Large-scale projections include weirs, cavities and regular periodic profiles with larger amplitudes. As with small-scale geometry, these wall changes alter the velocity profiles, turbulence and interface location of the film and may cause perforations. Perforations may be created at the downstream side of a bump since bumps produce surface profiles with an upstream peak and downstream valley [109]. A thin film on a corrugated wall will assume a corrugated profile. These artificial waves will behave differently then other waves as part of their volume is a solid surface. Experimental findings also suggest that even relatively thin films on periodic walls can develop additional disturbances in the form of small bulges downstream of the wall troughs [110, 111]. Weir flow is commonly encountered in oceanic flows or may be used to initiate the flow of a film in an experimental setting. Weirs often behave as the bumps discussed above. Large cavities can cause film separation as the liquid tried to navigate the corner. More moderately sized cavities may create an artificial trough in the film, a sudden change in film thickness (with the interface remaining level downstream of this jump, even after the cavity ends) and/or bulges like solitary, stationary waves either upstream or downstream of the cavity [112].

Angled walls are generally only studied from an oceanic perspective, where waves form and break on a beach [63, 66]. In this case, the wall is angled inward and causes the film the thin. Even if waves do not appear due to the interaction of liquid structures and the angled wall, it is possible to create a stationary disturbance through a hydraulic jump. Outwardly angled walls cause the film to thicken; they can lead to film separation as the film attempts to navigate the corner or act as a turbulence trip. In rare cases they can lead to cavitation and may create disturbances as discussed in the Pressure Fluctuations subsection of disturbance formation.

Qualitative theories for predicting the interface profile or velocity profile of a film when the wall is not flat and level are scarce; a wider variety of experimental studies of interface profiles appear in the literature. However, studies and theories generally exist only for falling films, films flowing on inclined surfaces under the action of gravity, velocities in the Stokes flow regime or oceanic (i.e., relatively deep) flows. None of these situations are commonly encountered in atomizers and in these studies atomization is generally absent or incidental. To further complicate the development of predictive tools, the resulting disturbances greatly depend on the geometry of the wall, the relative thickness of the film and the velocity of the film; even for a given geometry and conditions, multiple surface profiles may be possible [113]. No literature was found in which corrugated walls or other wall geometry was used as a mechanism to aid atomization. Still, the possibility is discussed here for the sake of completeness.

Perforations

Perforations occur in sheets and films and in stretched membranes created in some types of jet atomization. Sometimes these perforations are precipitated by localized thinning [36] due to gas structures (streamwise vortices, for example [36]) or more global stretching of the sheet or membrane due to imposed gas flows as in "bag" breakup [6]. A limited amount of work exists on this stretching mechanism, but other explanations have been offered as causes for perforations. Fraser et al. [37] observe holes in sheets and suggest that solid particles in the liquid, gas release in the form of bubbles within the sheet, droplet impingement or ripples may cause perforations. They try various experiments to elucidate the mechanism(s) involved and conclude that bubble release and droplet impingement are unlikely. Even more than forty years after Fraser's work no definitive experimental evidence as to the validity of these potential causes was found in the literature. Hydrodynamic instabilities have also been pegged as a possible cause of sheet perforations [10, 76] and may be responsible for the ripples observed by Fraser et al. [37]. Indeed, ripples are reported in many sheets prior to holes forming and to date appear to be the most likely cause in sheet flows without stretching.

Wall-bounded flows have a few additional mechanisms. Wall imperfections or purposely introduced "bumps" in the wall may cause holes to form. Films also may "spontaneously" rupture or dewet due to microscopic surface imperfections or forces on a molecular level [41, 42]. Films are commonly seen to split as they flow down inclined or vertical walls forming rivulets often due to spontaneous dewetting. Rivulet formation and stability is important in cooling towers where a break in the film can cause hot spots and failures [114]; consequently, many theories and correlations have been developed to predict the stability and formation of rivulets on inclined surfaces [114, 115]. In these examinations the gas and liquid flow rates are generally considered to be very small, unlike flows in most atomizers. Rivulet formation has also been observed on the surface of rotating cups and disks and a theory exists to calculate their formation [116]. Film perforations may also be caused by macroscopic wall features such as individual points or bumps [109], but this method appears to get little use or study as most literature deals with situations where perforations are undesirable. Perforation initiation remains largely unexplored in the atomization literature despite its possible importance for flows of metal and polymer melts where the liquid-solid surface tension which opposes hole growth may be small.

A thick rim is formed around an expanding hole [37, 117] which contains much of the liquid which used to occupy the hole (see Fig. 10a). Sheet perforations are closed circles or ovals while holes in flowing films take on parabolic-like shapes with thickened rims [115, 118] (Fig. 10b). This change in topology is important, and this rim may be the key disturbance instrumental in any further breakup. This raised area can break down via any of the breakdown categories. Perforations may break down via other means as well, as discussed specifically in the perforation breakdown category. While the perforation may be precipitated by already discussed causes, such as hydrodynamic instabilities, the growth rates of their rims will differ greatly from the growth rate of other disturbances. Numerous studies of hole growth rates have been conducted [42, 115, 119, 120].

Particle Formation—Bubbles

Gas bubbles can be formed due to the entrainment of air, by a gas coming out of solution or by vapor bubble formation (cavitation or boiling). Gas can also become trapped by a variety of mechanisms which are generally due to the breakdown of other disturbances. Several authors discuss gas entrainment due to breaking waves [121-123], for example. Both spilling and plunging breakers, described in the Disturbance Breakdown section, entrain air and create a number of bubbles in the liquid near the breaking event. However, the experiments seem to indicate that smaller waves produce fewer bubbles [122, 123]; most studies are of waves on the scale of those found in oceans not those found in atomizers. The collision of a droplet or collapsing ligament with the film may also entrain air [124]. Gas-phase eddies impinging the surface can create capillary waves which entrain bubbles at their troughs when their amplitude is above a certain threshold [124]. As with breaking waves, small amounts of air and, consequently, few bubbles are produced by these events. Woodmansee and Hanratty [125] mention air entrainment due to the interaction of ligaments and waves, perhaps via ligament collapse. There is also the possibility that gas-phase turbulence could cause deformations of the interface and lead to air being entrained in a manner similar but backwards to the creation of ligaments from liquid turbulence.

Lefebvre [5] discusses taking advantage of dissolved gases and/or boiling in a section on effervescent atomization, a term which is now used somewhat differently. In today's common usage, effervescent atomization involves gas being purposely introduced into the liquid, as discussed above, while flash atomization is used to identify the process involving boiling, cavitation or dissolution. If the gas is purposely introduced into the flow and the flow is not choked at the injector nozzle, bubbly flow will result. A change in pressure or temperature along the liquid could cause dissolved gases to come out of solution also forming bubbly flow. A hot wall or hot gaseous environment could cause the liquid to boil producing vapor bubbles. Also, cavitation in the nozzle could introduce pockets of vapor into the liquid, although these likely collapse quickly unless the liquid is in a state found in flash atomization [58]. Once gas or vapor bubbles are formed they may interact with the gas-liquid interface likely leading to some droplet production (see Fig. 16) as discussed in the Particle Interaction Breakdown section below. The gas may also stay within the liquid for long periods of time; Woodmansee and Hanratty [125] observed that gas did not have a strong tendency to escape the film but accumulated to rather large concentrations.

Disturbance Breakdown

Disturbance breakdown is the formation of a discrete parcel from a disturbance. This parcel could be a small droplet from the tip of a ligament or a large ligament from the downstream edge of a sheet or numerous sizes in between. The following discussion of disturbance breakdown is partitioned based on the category of breakdown as given in Table 4. Surface breakdown consists of several subcategories given in Table 5.

<u>Instability</u>

Here breakdown results from the continued growth of the disturbance to a point where the interface contacts itself, another interface or the wall. The two most common occurrences of instability breakdown are the bulk fluid mode of sheets when dilational waves (Fig. 4a) are present and Rayleigh breakup of jets or ligaments. In both of these examples, instabilities grow until the interface contacts itself or another interface (Figs. 2a & 4a): the existence of instabilities in the most common cases leads to the title choice. However, the growth of waves due to gas flowing over their curved surface or due to changes in wall geometry could also cause this category of breakdown.

This mechanism has been observed and described in much of the jet literature [6-8, 10-14], a large body of sheet literature [10, 12, 31] and by several investigators studying atomization due to liquid turbulence where the ligaments created by the turbulence break down in this manner [1, 65, 68]. Experimental comparisons based on instability growth rates and wavelengths have been favorable in all three of these situations [1, 10, 12, 14, 31, 65, 68]. No experimental evidence for instability breakdown was found in the film atomization literature, but it is possible. However, when instability breakdown occurs in films a wall-bounded discrete parcel (rivulet) results instead of a free ligament. Because this rivulet wets the wall surface, its breakdown differs from the ligament formed in sheets. The rivulet is less likely to produce droplets than the ligament. The further breakdown of the rivulet would fall into the discrete parcel class.

Instability breakdown can be modeled by considering the growth rate of the disturbance and tracking the interface. If the growth causes the interface touches another object (itself, other interface, wall) separation occurs and a discrete parcel is produced via this category. If forces tear or otherwise move the interface before pure disturbance growth causes the interface connection then another category describes the breakdown. Again, for the jet class the created parcel is a droplet; for sheets the parcel is a ligament the width of the sheet; for a film the parcel is a rivulet the width of the film.

Stripping

Stripping is the most commonly considered type of droplet formation from a liquid surface. This category occurs when lift or drag strips a portion of liquid from the bulk. (Interestingly, a similar category of breakdown occurs in electrosprays via electric forces instead of aerodynamic forces [126, 127].) This portion may be the tip of a wave or ligament [125, 128, 129] or a large section of the liquid at the downstream edge of the core [10, 12, 31]. Figure 11 illustrates stripping from a wave tip, and Fig. 4b shows stripping from the downstream edge. In general, stripping from the downstream edge is the slow form of this category of breakdown resulting in bulk fluid mode or the large droplets found in the mixed mode while stripping from a disturbance tip is a faster type responsible for smaller droplets.

Stripping from the downstream edge of the liquid is typified by such classic regimes as first wind-induced and sinusoidal wavy sheet. Aerodynamic forces on the liquid increase as the height of the disturbance increases. Stripping occurs because these aerodynamic forces (principally drag in this case) become larger than viscous and surface tension forces. Wave growth can upset the balance of forces leading drag to become important and tear away a part of the core, as when a half wavelength section of sheet tears from the bulk [32, 34, 77, 130]. The first wind induced regime was also meant to describe this combination of disturbance growth (due to instabilities) and stripping. This process can be modeled by a force balance, particularly at the troughs and crests of waves. More details on modeling are given for stripping from disturbance tips. These tip models could easily be modified to consider the balance at a wave trough instead of over a deforming section of a disturbance.

Stripping from the tip of a wave or ligament is a frequently described and studied type of breakdown ([125, 128, 129], for example), particularly in films where only a surface mode is considered. Here again, the aerodynamic forces (lift and drag) overwhelm the restoring forces (usually viscous and surface tension) once the disturbance reaches a particular size. Unlike stripping from the downstream edge, this occurs when the disturbance is still small compared to the characteristic dimension of the liquid or over a small section of a disturbance which has been distorted by the air flow (see Figs. 2c & 3c). The quantitative application of this mechanism is hindered by a number of factors, but comparisons of semi-analytic derivations with experimental results show promise [39, 52, 129]. Predictions are based on a force balance over the disturbance or a distorted section thereof. Uncertainties in application are rife, however, and arise from a lack of knowledge and predictive capability: for example, the distribution of wave/ligament sizes, their relative velocities and their shape are rarely known. A main uncertainty is knowing when, i.e., at what disturbance height, and how much liquid is sheared from the film. Holowach et al. [39] suggest that the maximum amount of lost liquid occurs when the forces on the distorted wave tip are evenly balanced; Mayer [128] assumes waves break off when the amplitude of the wave equals its wavelength; Woodmansee and Hanratty [125] observed that secondary waves separate from the main wave due to variations in air pressure induced by the flow over the waves. In reality, there is some probability that a disturbance will lose mass due to stripping, one that increases with amplitude and relative velocity between the liquid projection and the gas. Also, there is some range of mass that can be sheared from the projection. Because of this range of possibilities, analyses like Holowach et al.'s [39] that look for a maximum are especially appealing.

Surface

Surface breakdown occurs when a portion of the disturbance is lost while some portion of the disturbance generally remains attached to the bulk of the liquid. In general, surface breakdown occurs when the disturbance is relatively small and contributes to surface mode atomization. Surface breakdown often takes place in mixed mode atomization as well, with the small scales resulting from surface breakdown and the larger scales often resulting from instability or stripping breakdown. When occurring from a disturbance tip, stripping (discussed above) is in the surface category of breakdown; due to its other form (in the bulk fluid mode), however, it merits its own category. Surface breakdown encompasses other subcategories as given in Table 5. Upon further investigation, however, the first two subcategories—wave breaking and bag breakdown—are shown to be encompassed in other combinations of formation and breakdown categories. Because they appear in various literature dealing with atomization, they are discussed here as separate subcategories. When atomization models are developed, however, they can be portrayed by models describing other categories.

Wave Breaking

Growing waves can reach a size where they are no longer self-supporting, particularly if the liquid is bounded by a wall. Wave growth is generally caused by aerodynamic enhancement or wave-wave interaction [121], such as coalescence, but can also be caused by changes in the wall geometry. Waves that are no longer self-supporting will break, as waves do on a beach. Two main types of breaking waves exist: spilling and plunging. Spilling breakers occur in the small wavelength waves expected in atomizers and are characterized by a capillary-gravity "bulge" on the front-side of the wave which, eventually, leads to turbulence on the downstream/leeward side of the wave [131]. This turbulence could generate additional disturbances through the liquid turbulence category of disturbance formation, but does not produce droplets itself. Plunging breakers create a jet which plunges into the film ahead of the wave [131]. This type of breaking is more energetic than spilling and droplets are created from the interaction of the jet with the film, similar in many ways to splashing during droplet impact [121]. Figure 12 illustrates the two types of waves just prior to breaking. Studies of turbulent liquid films [65] have observed ligament collapse producing droplets in a mechanism similar to the jet collapse in plunging breakers [124]. Both studies of turbulent film jet collapse and breaking waves conclude that this mechanism creates only a small number of relatively small droplets. Indeed, numerical models from the literature suggest that each plunging breaker would produce a very limited number of droplets [121]. Both types of breaking do entrain air, however, which may lead to atomization through bubble collapse [121, 124, 131]; still, bubble rupture creates a fine spray and a few larger droplets, so many bubbles would be required to burst before appreciable atomization would occur. Splashing due to ligament collapse and bubble rupture all fit into the Particle Interaction subsection and disturbance formation via bubble creation or turbulence due to wave breaking would fall into previously presented formation categories. All of these findings suggest that wave breaking in atomizers is not a primary means of disturbance breakdown particularly as wave stripping theories suggest few waves would grow to a size to break due to mass loss via stripping. The findings also suggest that wave breaking as a means of disturbance formation or breakdown is encompassed in other categories.

Bag Breakup

In a mechanism that, in part, resembles wave breaking [121], the wave may be undercut due to liquid or gas eddies at its base. This undercutting causes the wave to fall in a manner that resembles wave breaking but occurs with less speed and a smaller mass of liquid. Consequently, an open air pocket can be formed between the wave and the surface. The motion of the liquid entrains air into the pocket, causing it to grow. Eventually, the air pressure inside this “bag” causes the pocket to catastrophically fail producing small droplets and a thick rim at the pocket’s upstream edge. This rim then devolves to droplets via the Rayleigh mechanism. Parallels can be drawn between this process and “bag” breakup of droplets (parcels) and jets or the stretched-streamwise ligament regime in sheets [40]. This process is shown schematically in Figure 13. Azzopardi [40] reports observing it in a study of annular, vertically upward film flow. Woodmansee and Hanratty [125] find atomization via a very similar process, also in films. In their experiments, they observe a secondary wave accelerating and partially separating from the film to form a thick ligament (possibly due to aerodynamic forces in a process similar to stripping). This ligament is stretched and thinned by the air flow until it ruptures. Due to their under-film imaging technique and the relatively thin nature of the bag there is a possibility that the ligaments observed by Woodmansee and Hanratty [125] had attached thin films and that their results indicate bag breakup for flat films as well as the bag breakup observed by Azzopardi [40] for annular films. No further descriptions or evidence of this mechanism in sheets or jets was found in the literature. In many regards, this may be more of a formation mechanism as the breakup is essentially a small-scale mixed mode where the rupture of the membrane produces small droplets (perforations) and the breakdown of the bounding ligament produces larger droplets via a different category of breakdown.

Turbulent Undercutting

The experimental studies of Sarpkaya [132] dealing with film atomization due to liquid turbulence found that some ligaments detach from the film at their base. He hypothesized that turbulent eddies at the base of these ligaments cause them to separate from the liquid. This study and others, also in air-water systems, investigating turbulent-liquid flow showed that most ligaments break up due to instability breakdown (via a Rayleigh mechanism), but that some undergo this turbulent separation [1, 132]; both sets of experimenters estimate that 90% of ligaments undergo instability breakdown and 10% undergo separation due to eddy interaction. For different liquid-gas combinations this percentage may change. The droplets produced by this method are much larger than those created by instability breakdown because they contain nearly the entire volume of the ligament. Investigations of ultrasonic atomization may shed more light on this process. Wall movement results in changes in liquid velocity which cause drainage near the ligament base leading to thinning and rupture [133]. Perhaps liquid eddies create a localized velocity inversion draining and rupturing the lower portion of the ligament. If the size (and, hence, volume) of the ligament is known, the size of the resulting droplet can be calculated. No prediction of when and where this turbulent separation will occur can be given, but the location and frequency of shedding may be dealt with in a stochastic manner. Figure 14 shows this type of breakdown.

Fragile Shattering

Fragile shattering occurs when the liquid is unable to react (by deforming) to its surrounding unsteady flow because the required speed of deformation exceeds the speed of liquid molecule relaxation [134, 135]. Because the fluid is unable to relax quickly enough it acts, essentially, as a solid. This type of breakup is illustrated in Fig. 15. Khavkin's [134] theoretical examination of secondary droplet breakup concerned flow in pressure swirl atomizers where the droplets were subjected to uneven force loading due to the centripetal forces, which acted to deform the droplets. If the viscosity of the liquid is sufficiently large it delays this relaxation; consequently, the liquid reacts like a solid and shatters. Ligaments subjected to swirl or other nonuniform velocity fields could also undergo shattering if their viscosity and the forces acting on them were large enough. At this time, however, the existence of this mechanism in ligaments remains speculation. It has, however, been observed in secondary droplet atomization in accelerating flow fields [135].

Perforations

Rupturing of a thin membrane is the most common example of droplets produced by perforations. This occurs in any of the numerous “bag” breakup regimes cited in the literature, and is analogous to the rupture of a bubble at an interface. Here perforations form and rapidly expand briefly creating a series of discrete-parcel-class ligaments which then further break down into fine droplets. On a larger scale, numerous works deal with perforations which grow more slowly and result in a series of ligaments connected to the bulk liquid ([36, 37], for example). Similarly, film studies report both discrete-parcel-class [41, 42] and attached ligaments [114, 115, 136], but in films they are all wall-bound; no gas-surrounded parcels are reported to result from perforations.

Above a particular size, generally small [119], holes in sheets rapidly grow larger due to surface tension forces; holes in films may grow, shrink or stabilize [117, 136]. Only stable or expanding holes are of interest here as shrinking holes do not lead to atomization. As discussed in the Disturbance Formation section, the liquid which used to occupy the hole forms a raised rim bounding the perforation; this rim can break down via other categories of breakdown. Another mechanism for droplet production may be the collision of these raised rims. Collisions are more likely to produce droplets in sheets than in films due to the relatively slower growth rate of film holes. Slower growth rates mean rim collisions have less energy for producing air-borne droplets. The process by which rim collision produces droplets is not understood, but could resemble splashing events, particularly corona splashing where a tall, narrow disturbance is briefly formed. At slow speeds colliding rims may behave like coalescing waves. This would lead to a temporary increase in the rim's size which may increase the likelihood of other types of breakdown, particularly stripping. To date nothing of this nature has been observed; indeed, no study of rim collision mechanics was found in the literature.

Perforations may also act locally on a disturbance. For example, the complex three-dimensional gas structures (streamwise vortices), such as observed by Stapper et al. [36], might cause single waves or the edge of a sheet or film to split into multiple disturbances. While this process may not produce droplets, the breakdown of the resulting disturbances would differ from the breakdown of the original. Locally acting perforations may also explain the formation of ligaments at the edge of a sheet formed by impinging jets or the fingers produced in corona splashing, although this seems somewhat unlikely.

"Particle" Interaction

Discrete objects may interact with the interface. Two types of objects are considered here: bubbles and droplets. Ligament collapse is considered to be sufficient like droplet collision to not require a specific discussion here. Bubble creation was considered above while this entire paper is focused on droplet formation. When bubbles contact an interface they may rupture creating a collection of very small droplets and possibly leading to the creation of a ligament and a few large droplets. While the formation and evolution of the ligament is different, the end result is not unlike the bag breakup regime of jets or the stretched streamwise ligament regime of sheets. Atomization due to this process has been studied for quiescent and slow moving films such as oceanic flows. Droplet collision produces other droplets through splashing, which may take several forms. Droplet impingement on walls and films has received a lot of attention in terms of heat transfer and the removal of droplets from the gas, but less in terms of atomization. Neither bubble rupture nor droplet splashing has attracted much attention in terms of jet and sheet atomization (although Fraser et al. [37] studied the possibility that droplet collisions caused perforations, they concluded that in their experiments collisions were not a factor). Exploration of the literature suggests that neither mechanism will be of primary importance when the goal is to fully atomize the liquid. Still, droplet collision and bubble rupture can create droplets that contribute to the overall spray characteristics. Not considered here, but of importance in special cases, is the possibility of solid particles interacting with the surface. Solid particulates could cause splashing, as droplets do, or they could alter the interface properties via surface contamination.

Bubble Rupture

If a bubble contacts a liquid interface, droplets and projections may be created through their bursting or rupturing as shown in Fig. 16. Two types of droplets can be created [137-139]. Film drops are created by the bursting of the thin film formed between the top of the bubble and the gas. Film droplets are very small, on the order of a few microns [137, 139]. The second type of droplets, jet drops, form from jets created by the collapse of the bubble cavity. Jet droplets are tens to hundreds of microns in diameter [137, 139]. Not all of the jets created by bubble rupture result in the formation of droplets; bubbles must be *below* a critical size for their collapse to produce a jet that devolves into one or more droplets [138]. "Jet" is the typical nomenclature for this disturbance, and it does resemble the jet class, it is just smaller than most of the jets considered in atomization literature.

The process of jet formation due to bubble rupture has been studied experimentally ([140], for instance) and numerically [137, 139] with good agreement between the two. Jet production proceeds through the following stages. First the bubble cap ruptures leaving a cavity in the surface of the film. A series of capillary waves are formed which converge to the base of the cavity. This convergence may trap small, compared with the initial bubble size, air bubbles. The interaction of these waves generates a ligament in the center of the original cavity. This ligament then breaks down into one or more droplets [137, 139]. Generally the ligament is assumed to break down as in the instability category, but it could, in principle, be fragmented by the other breakdown processes. It may also collapse back into the film without creating any droplets. Because bubble rupture creates several extremely tiny droplets and, at most, a few droplets (the jet drops) of a size expected in atomization, it is not projected to be of primary importance if large portions of the liquid are atomized.

Splashing

The collision of droplets with a liquid film is an entire subject of its own. Studies centering on atomizing flows are rather limited, however, with consideration generally given to the impact of a single droplet with a film where the creation of the initial colliding droplet and the behavior of ejected droplets are given little or no consideration. This lack of focus on atomizing flows may be the result of earlier findings by Woodmansee and Hanratty [125] that splashing was of lesser importance than other droplet creation mechanisms when considering atomization. More likely, however, it is a result of the complexities and on-going evolution of knowledge of single droplet collisions with films. When a droplet collides with a liquid interface it may bounce, merge or create secondary droplets [141]. Secondary droplet creation takes one of three main forms: partial absorption, corona splash or prompt splash [141, 142]. These three forms are presented in Fig. 17. Partial absorption occurs when the droplet initially merges with the film, but a single, wide projection is subsequently created. This ligament leads to the creation of a single, smaller droplet [141]. Corona or crown splashing is the type which often appears in photographs. In this kind of splashing a thin liquid sheet is created shortly after the droplet impacts the surface. This sheet spreads radially outward and generally develops into fingers which break in the instability category (due to Rayleigh instabilities) [142]. Here a central ligament may or may not be created and may break into one or more droplets. As with partial absorption, smaller droplets are produced. The last type of secondary droplet creation is prompt splash which, like prompt atomization, takes place immediately after impact without any observable sheet or jet [142]. The values of the Reynolds and Weber numbers of the colliding droplet determine whether a secondary droplet is created and which form the creation takes; as Reynolds and Weber numbers increase the collision result changes from absorption (no droplet creation) to partial absorption to corona splashing to prompt splashing [141, 142].

Splashing can also occur when liquid projections, such as ligaments, collapse. Studies of ligament collapse during the atomization of turbulent liquid films have revealed that, in this configuration, splashing creates only a few very small droplets; additionally, ligament collapse appears to be less common than ligament breakup [65, 124]. Indeed, splashing is unlikely to be an important droplet creation mechanism in atomizers where the goal is the transformation of the entire film to droplets, in part because the initial droplets must come from somewhere and the atomized mass is almost always less than the impacting mass. Also, in atomizers the intact liquid exists for a relatively short distance limiting the number of collision events. In situations where atomization is not the primary goal, such as in cooling tubes, the liquid may be intact over a larger length increasing the importance of splashing. The overall lower number of droplets and a greater likelihood for secondary droplet dynamics (such as coalescence) may also increase the importance of droplet creation due to splashing in situations other than atomizers.

Conclusions

A new, device-independent view of the atomization process has been presented here. Liquid undergoing atomization is classified based on its geometry just prior to breakup instead of the traditional classification of atomization by atomizer type. The classes are jet, sheet, film, prompt and discrete parcel. In jet, sheet and film, the liquid is being replenished from an upstream feed and an intact, visible length of liquid exists. Jets, sheets and films differ in the number of interfaces (jet has one, sheet as two) and the possible existence of a wall (films are bounded by one wall). In the prompt class, breakdown is such that no intact core is formed; the discrete parcel class, meanwhile, encompasses discrete liquid objects such as droplets and ligaments. Across these classes, atomization may be divided into modes based on the time-scales involved in the process of disturbance growth and breakdown or, equivalently, based on the relative size of disturbances and created droplets compared to the characteristic bulk liquid dimension. The view here is that the liquid geometry determines the injector class while the operating conditions contribute primarily to the atomization mode, which is more global and basically independent of class. Large disturbances, on the order of the characteristic bulk liquid dimension, typify the bulk fluid mode while the surface mode involves small disturbances and small droplets. The mixed mode contains multiple scales and may be a transitional mode between the two extremes. Several traditional atomizer classifications and breakup regimes have been considered in the context of this framework. (Examples of correspondences between the traditional and new systems are given in the Appendix.)

At its most basic, the atomization process may be described as the creation and growth of disturbances followed by their breakdown into discrete parcels. Various categories of disturbance creation and disturbance breakdown were considered. Liquid structures, hydrodynamic instabilities, gas-phase structures and pressure fluctuations as well as perforation causes and the formation of particles, specifically bubbles, were the considered creation categories. Turbulent liquid structures and hydrodynamic instabilities have received the most attention in the literature and are often the most likely causes of disturbances. However, when the gas is dense or very energetic structures are formed, it cannot be neglected as a source of disturbances. Pressure fluctuations are more likely to change the evolution of disturbances, but may lead to solitary waves if they affect feed velocities. Wall effects have not been studied but only occur in very specialized cases. No mechanism seemed likely to produce large numbers of bubbles in atomizers; on typical atomizer scales bubbles are most likely if gas is purposefully introduced or the liquid is purposely boiled. Instabilities appear to be the most likely cause of perforations in sheets and relatively thick films, but no definitive culprits for perforations of atomizing liquids have yet been found. In thin films, wall imperfections may play a key role in the formation of holes.

The categories of disturbance breakdown are instability, stripping, surface, perforation and particle interaction. The surface category encompasses four subcategories of wave breaking, bag-breakup, turbulent undercutting and fragile shattering. However, more detailed investigation showed that wave breaking and bag breakup are basically encompassed in other categories. The particle interaction considered here was splashing due to droplet impact and bubble rupture; solid particles may interact with the liquid in some unusual cases but were not considered here. Instability and stripping occur in the bulk fluid mode; any of these categories may occur in the surface mode. Combinations generally occur in the mixed mode. For atomizers operating in a surface mode with strong aerodynamic forces, stripping or bag-breakup are the most likely. If aerodynamic forces are less important then instability breakup of small ligaments often occurs. Depending on the gas-flow conditions, fragile shattering is a possibility although it has not yet been observed experimentally. Wave breaking, splashing and bubble rupture are only likely to be small contributors to atomization in most cases of practical engineering interest, in part because they all produce relatively few droplets per event. Perforations in sheets are likely to produce droplets through the collision of their rims or, if very thin, in a manner akin to the production of film drops in bubble rupture. Film perforations are less likely to be catastrophic and droplet production likely results from the breakdown of the raised rim of the hole via other breakdown categories.

This approach, while very general, encompasses the majority of atomization physics described in the literature when wall and nozzles are rigid and imposed body forces are not employed. This generalized approach allows an additional understanding of atomization processes to be developed. It also highlights how limited the understanding of some aspects of atomization remain. By identifying weaknesses that exist throughout the field, across the traditional atomizer types, profitable areas of future research are uncovered. Finally, the fundamental framework developed here suggests that a relatively small number of models could be developed to quantify the atomization process in a wide range of devices.

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Appendix

Additional material is provided familiarize the reader with the classification system. This material should also aid in the classification of new atomizers or those not covered in detail within the text. The glossary reinforces the particular and specific keyword conventions used throughout this work. Tables 6 and 7 present correspondences between traditional groupings and the current class-mode framework.

Glossary

Bag Breakup: A type of surface breakdown which is characterized by a thin bag-like membrane bounded by a thick ligament rim and the bulk liquid

Bulk Fluid Mode: An operating mode characterized by disturbances and subsequent discrete parcels which are large compared to the characteristic dimension of the liquid

Category: A facet of the framework used to describe the physics underlying disturbance behavior; there are two subsets of categories—disturbance formation and disturbance breakdown

Class: A facet of the framework which captures the geometry of the liquid just prior to atomization

Discrete Parcel: A class of atomizers where the liquid is not attached to a feed system, having already separated from one of the other classes of atomizers (secondary atomization is a subset of this class)

Disturbance: A wave, ligament, perforation, etc which is an altered topology to the interface

Disturbance Breakdown Category: A facet of the framework which uses the underlying physics describing the actual liquid removal process

Disturbance Formation Category: A facet of the framework which divides the causes of disturbances based on the underlying physics involved with their creation

Film: A class of atomizer characterized by a liquid with one (of multiple) interfaces in contact with a wall (Figs. 1e & f)

Fragile Shattering: A subcategory of surface breakdown wherein the inability of a liquid to adapt to the flow field through relaxation results in the liquid behaving like a solid and shattering into several discrete parcels

Gas Structures: A category of disturbance creation resulting from the interaction of turbulent or organized (e.g., recirculation vortices) gas-phase structures with the interface

Hydrodynamic Instabilities: A category of disturbance creation wherein growth is a result of the hydrodynamic instabilities of the flow

Instability Breakdown: A category of breakdown caused entirely by the continued growth of a disturbance

Jet: A class of atomizer characterized by a liquid with a single characteristic dimension (Fig. 1a)

Ligament: A disturbance which is higher than it is wide (chosen for the purposes of clarity in discussion only)

Liquid Structures: A category of disturbance creation resulting from the interaction of liquid structures (turbulent or organized) and the interface

Mixed Mode: An operating mode where two or more different scales of disturbances and discrete parcels are created

Mode: A facet of the framework which describes the character of the liquid core and produced droplets; mode is dictated by the rate of disturbance growth compared to the rate of disturbance breakdown

Parcel: see Discrete Parcel

Particle Formation: The creation of a foreign body such as a bubble or discrete parcel (important if this particle goes on to interact with the interface)

Particle Interaction: The results of an object such as a bubble, discrete parcel or solid particle contacting the interface

Perforation: A hole or break in a film or sheet which does not directly create a discrete parcel; a localized meeting of an interface with another interface or the wall

Pressure Fluctuations: A category of disturbance creation resulting from changes in the pressure; this category encompasses cavitation

Prompt: A class of atomizers characterized by a feed system for the liquid, but a lack of liquid core

Sheet: A class of atomizer characterized by a liquid with two characteristic dimensions and multiple interfaces in contact with the gas (see Figs. 1b & c)

Stripping Breakdown: A category of breakdown caused by aerodynamic forces which drag or lift part or all of a disturbance from the liquid

Surface Breakdown Category: A collection of breakdown categories which can only lead to the surface mode of atomization

Surface Mode: An operating mode characterized by disturbances and subsequent discrete parcels which are small compared to the characteristic dimension of the liquid

Turbulent Undercutting: A subcategory of surface breakdown caused by the interaction of a turbulent liquid eddy with the base of a ligament

Wave: A disturbance which is wider than it is high (chosen for the purposes of clarity in discussion only)

Wave Breaking: A type of surface breakdown occurring when a disturbance grows so large that it is no longer self-supporting (e.g., breaking waves on a beach)

List of Tables

Table 1: A listing of the generalized classes of atomizers as illustrated in Fig. 1.

Table 2: Atomization modes, which are basically independent of atomizer class, are listed here and shown in Figs. 2, 4 & 6.

Table 3: The categories of disturbance formation are listed.

Table 4: A catalog of the categories of disturbance breakdown. Many of these are illustrated in Figs. 11-17.

Table 5: Subcategories of surface breakdown are given.

Table 6: Examples of traditional regimes are matched to the class and mode of the current framework.

Table 7: Examples of traditional regimes and atomizer types are given for the new class-mode pairs. The list is not exhaustive for a given traditional atomizer type (i.e., a type may not be listed in all the class-mode pairs in which it can operate).

List of Figures

Figure 1: Shown here are the five different classes of atomizers and some subconfigurations thereof. The five classes are (a) jet, (b) sheet, (d) film, (f) prompt and (g) discrete parcel. The annular subconfiguration of sheets and films are shown in (c) and (e) respectively. Another parcel shape is shown in (h).

Figure 2: Simplified diagrams illustrating atomization modes of jets—bulk fluid mode (a), mixed mode (b) and surface mode (c). The surface mode diagram (c) represents a close-up view of the jet in that mode.

Figure 3: Generalized sketches based on experimental results showing the modes of jets. Rayleigh breakup is shown in (a) and breakup in the first-wind induced regime in (b). Both are in the bulk fluid mode. The second wind-induced, or surface mode, appears in (c). Part (d) shows bag breakup of a jet in coflow (mixed). Lighter areas indicate thinner sections of liquid.

Figure 4: Simplified diagrams illustrating the three atomization modes for sheets—bulk fluid (a & b), mixed (c) and surface (d). The bulk fluid mode may occur in dilational (a) or sinusoidal (b) modes. The surface mode figure (d) represents a close-up view of a portion of the sheet.

Figure 5: Experimentally-based, general sketches of the atomization modes of sheets. The wave regime (bulk fluid mode) of an annular sheet is shown in (a). Parts (b) and (c) show the mixed (stretched-streamwise ligament) and surface modes respectively. The shade of color is an indication of liquid thickness.

Figure 6: Simplified diagrams illustrating the three atomization modes for films—bulk fluid (a), mixed (b) and surface (c). The mixed mode (b) is suggestive of a situation where discrete parcels are created from rivulets and stripping of the perforation's rim. The surface mode illustration (c) represents a close-up view of the film in that mode.

Figure 7: Effervescent (and internal flash) atomizers operate with the nozzle flow in one of the following traditional regimes: bubbly (a), slug (b) or annular (c)

Figure 8: Impinging jets (a) and their subsequent behavior are similar to jets impacting splash plates (b). These two configurations also share several similarities with a jet impacting a wall (c), despite the lack of a sheet in the wall-impact configuration.

Figure 9: Large–scale, coherent gas structures can, in some cases, affect the surface of a film. This illustration shows one way in which these structures can create disturbances. The spiral represents a clockwise-swirling vortex in the gas phase.

Figure 10: The liquid around a perforation takes on a raised profile. In sheets circular or oval holes are created (a) while in films open parabolic-like profiles result (b).

Figure 11: Examples of stripping due to drag (a) and lift (b), i.e. variations in air pressure due to flow over the curved wave, are shown.

Figure 12: Two types of breaking waves, spilling (a) and plunging (b), are shown just prior to breaking.

Figure 13: The profile of the film prior to and just after the rupture of the "bag" during bag breakup.

Figure 14: Turbulent base cutoff is shown along with the ligament prior to breakdown.

Figure 15: Shattering and the ligament prior to breakdown are shown.

Figure 16: The result of a bubble rupturing is shown here in a cut-away view. The central, created jet may or may not evolve to produce a droplet. The fine film droplets are not shown.

Figure 17: The three modes of droplet splashing are illustrated as well as the initial state prior to particle impact (a). The modes are partial absorption (b), corona splash (b) and prompt splash (c).

Classes of Atomizers
Jet
Sheet
Film
Prompt
Discrete Parcel

Table 1

Atomization Modes
Bulk Fluid
Mixed
Surface

Table 2

Disturbance Formation Categories
Liquid Structures
Hydrodynamic Instabilities
Gas Structures
Pressure Fluctuations
Wall Effects
Perforations
Particle Formation

Table 3

Disturbance Breakdown Categories
Instability
Stripping
Surface
Perforations
Particle Interaction

Table 4

Surface Breakdown Subcategories
Wave Breaking
Bag Breakup
Turbulent Undercutting
Fragile Shattering

Table 5

Traditional Type	Traditional Regime	Class	Mode
Jet in Quiescent Atmosphere	Rayleigh	Jet	Bulk Fluid
Jet in Quiescent Atmosphere	1st Wind Induced / Nonaxisymmetric Rayleigh	Jet	Bulk Fluid
Jet in Quiescent Atmosphere	2nd Wind Induced / Wind Stress	Jet	Surface
Jet in Quiescent Atmosphere	Prompt	Jet / Prompt[a]	Surface / N/A
Jet in Coflow or Jet in Cross-Flow	Rayleigh-type	Jet	Bulk Fluid
Jet in Coflow	Breakup via stretched-sheet mechanism	Jet	Mixed
Jet in Coflow	Breakup via fiber-type ligaments	Jet	Surface
Jet in Cross-Flow	Column / Arcade	Jet	Bulk Fluid
Jet in Cross-Flow	Bag	Jet	Mixed
Jet in Cross-Flow	Bag-Shear / Multimode	Jet	Mixed
Jet in Cross-Flow	Shear	Jet	Surface
Annular(Conic) Sheet	Bubble	Sheet	Bulk Fluid
Annular(Conic) Sheet	Sheet Collapse / Pencil	Jet	Generally Bulk Fluid
Flat or Annular Sheet	Wavy Sheet Mode (Sinusoidal, Dilational or both)	Sheet	Bulk Fluid
Flat or Annular Sheet	Cellular	Sheet	Mixed
Flat or Annular Sheet	Stretched Streamwise Ligaments	Sheet	Mixed
Flat or Annular Sheet	Surface	Sheet	Surface
Film	Surface	Film	Bulk Fluid
Droplet	Secondary Breakup	Discrete Parcel	Various

[a] See Atomization Classes and Modes-Prompt for arguments that this traditional regime does not truly fit into the current prompt class definition.

Table 6

Class-Mode	Traditional Regimes	Traditional Atomizer Types
Jet-Bulk Fluid	Rayleigh 1st Wind Induced / Nonaxisymmetric Rayleigh Rayleigh-type Column / Arcade Sheet Collapse / Pencil	Dripping faucet Plain orifice (start-up or low-flow) Jet in cross-flow (very low gas flow) Rotary (when jets formed) Simplex (start-up only) Electrospray
Jet-Mixed	Breakup via stretched-sheet Bag Bag-Shear / Multimode	Jet in cross-flow Shear coaxial (at air-flow rates between those producing bulk fluid and surface mode)
Jet-Surface	2nd Wind Induced / Wind Stress Prompt[a] (Jet) Breakup via fiber-type ligaments Shear	Jets in cross-flow Shear coaxial Plain orifice (all at relatively high flow rates)
Sheet-Bulk Fluid	Bubble Wavy Sheet Mode	Flat fan Simplex Impinging Jets (all at relatively low flow rates)
Sheet-Mixed	Cellular Stretched streamwise ligaments	Flat fan Simplex (at air-flow rates between those producing bulk fluid and surface mode)
Sheet-Surface	Surface	Flat fan Simplex Rotary Swirl coaxial (low end of typical operations) Prefilmer (low end of typical operations)
Film-Bulk Fluid	Not discussed in atomization literature	Rainwater on a window Some dip-coating operations
Film-Mixed	Not discussed in atomization literature	Shear-driven thin film flows Gas-centered swirl-coaxial (in a limited range)
Film-Surface	Surface	Oceanic flows Swirl coaxial Prefilmer Gas-centered swirl-coaxial Diesel with strong spray impingement (all at typical operating conditions)
Prompt	Prompt[a]	Drop-on-demand applications High speed jets and sheets[a]
Discrete Parcel-All Modes	Secondary Breakup	Droplet breakup Breakup of parcel (ligament) formed in Sheet-Bulk Fluid mode

[a] See Atomization Classes and Modes-Prompt for arguments that this traditional regime does not truly fit into the current prompt class definition.

Table 7

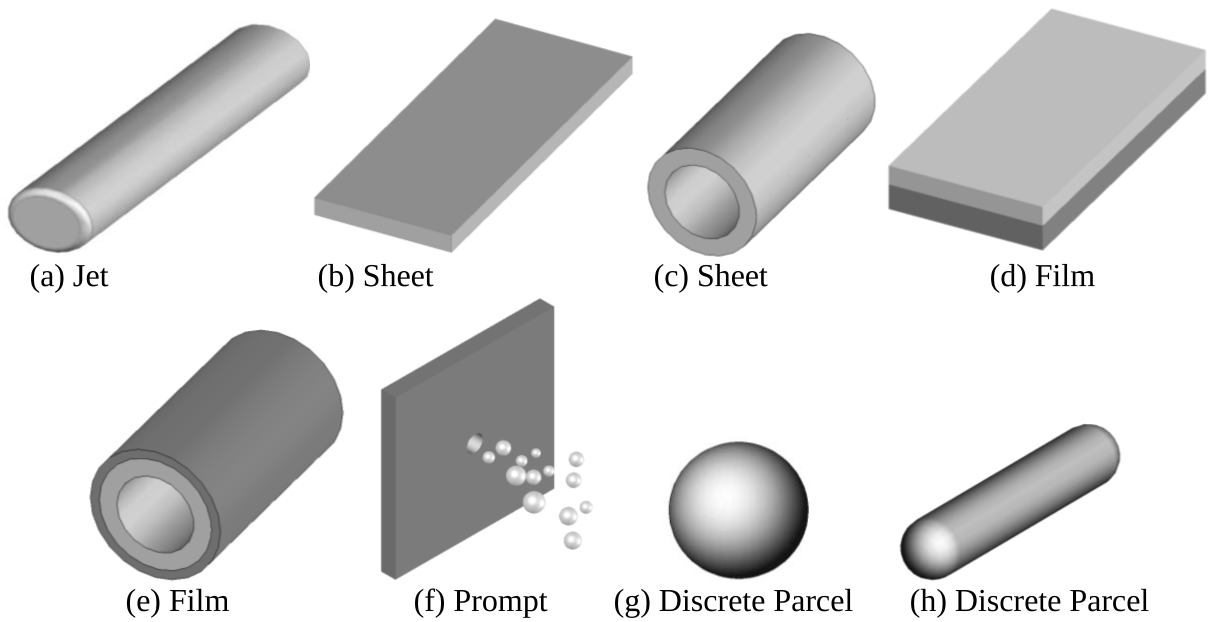
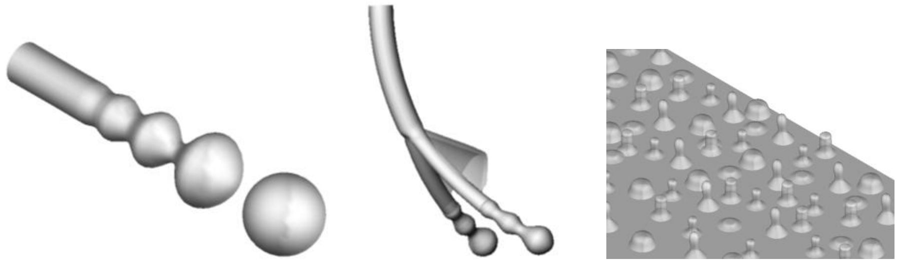
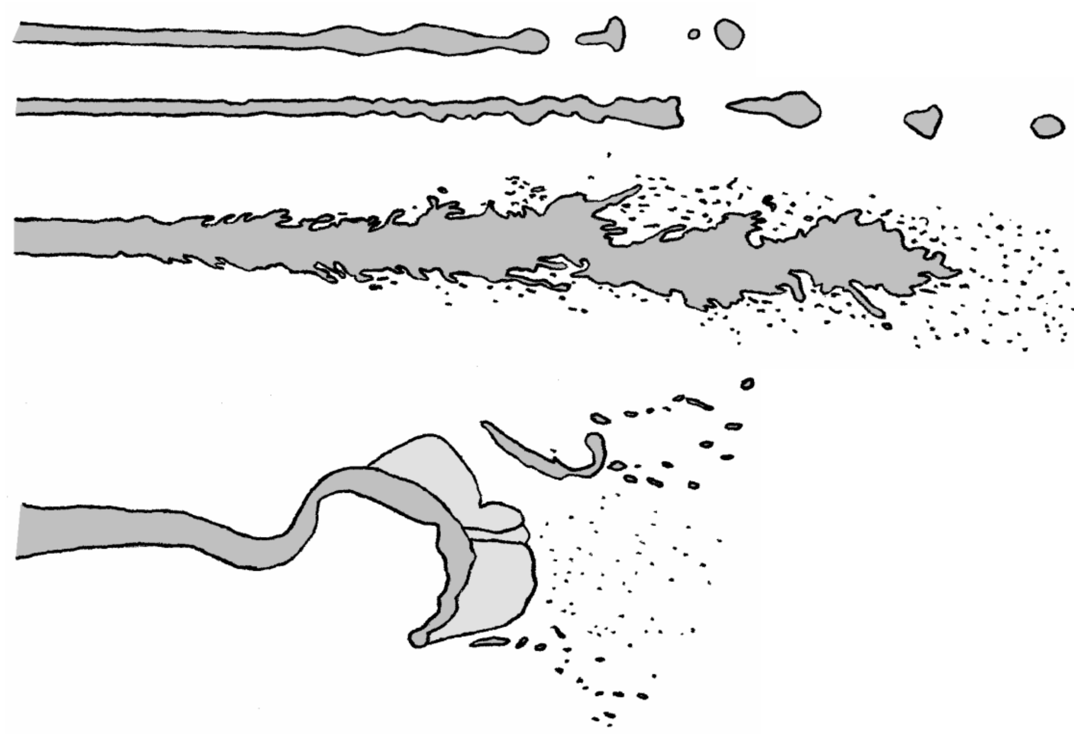

(a) Jet
(b) Sheet
(c) Sheet
(d) Film
(e) Film
(f) Prompt
(g) Discrete Parcel
(h) Discrete Parcel

Figure 1



(a) Bulk Fluid (b) Mixed (c) Surface

Figure 2



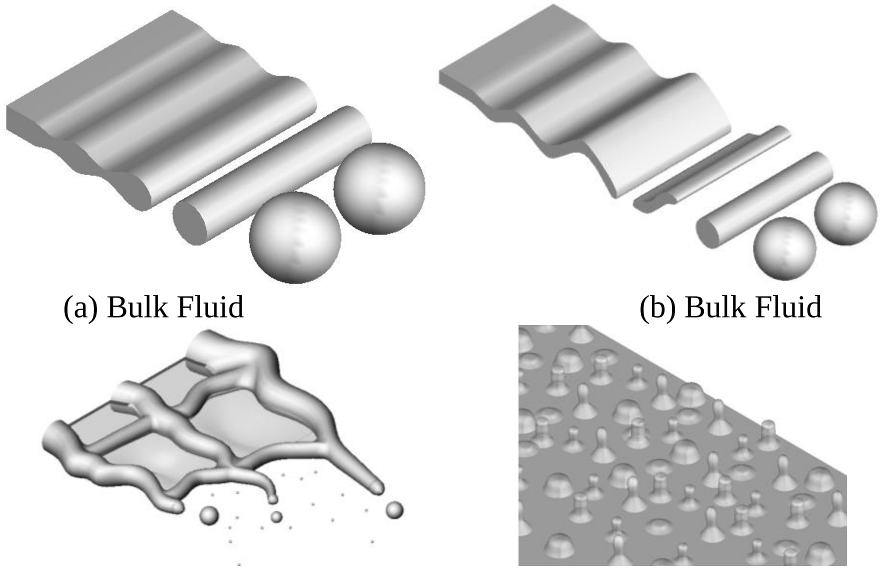
(a) Bulk Fluid

(b) Bulk Fluid

(c) Surface

(d) Mixed

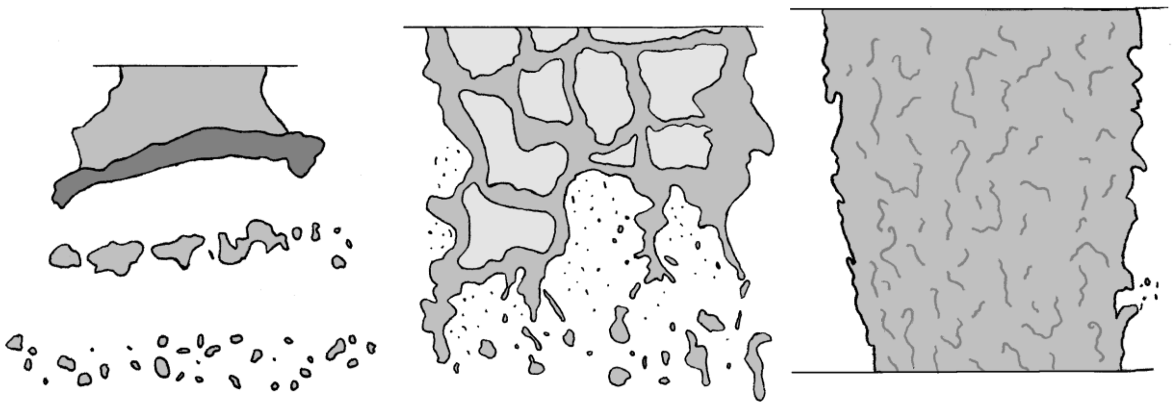
Figure 3



(a) Bulk Fluid (b) Bulk Fluid

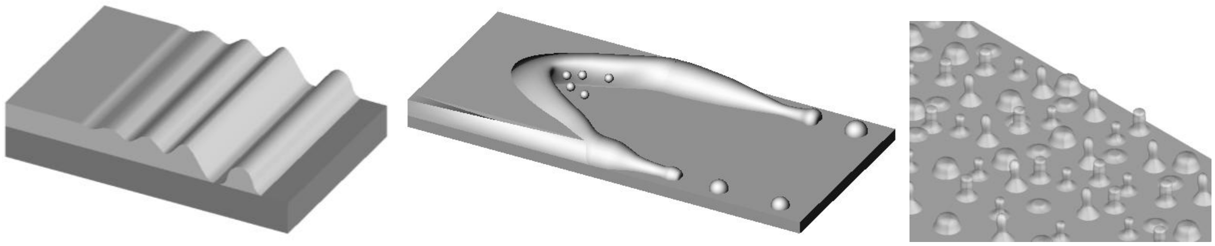
(c) Mixed (d) Surface

Figure 4



(a) Bulk Fluid (b) Mixed (c) Surface

Figure 5

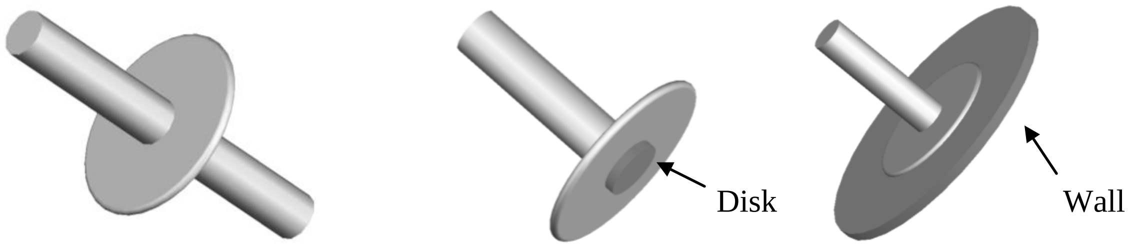


(a) Bulk Fluid (b) Mixed (c) Surface

Figure 6

(a) Bubbly (b) Slug (c) Annular

Figure 7



(a) Impinging Jet (b) Splash Plate (c) Wall Impingement

Figure 8

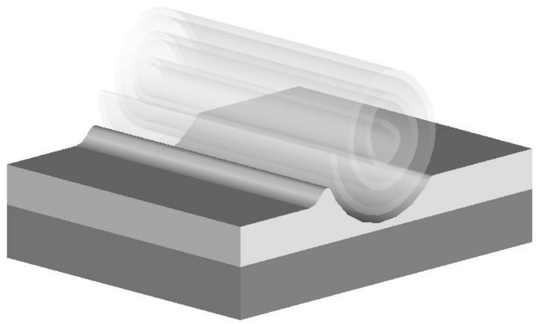
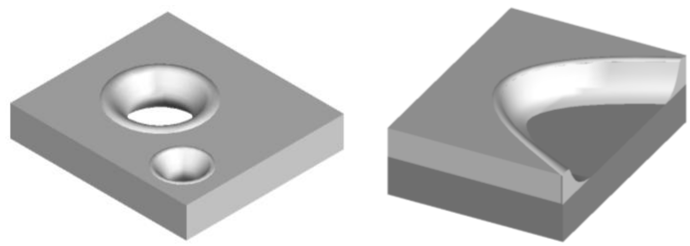
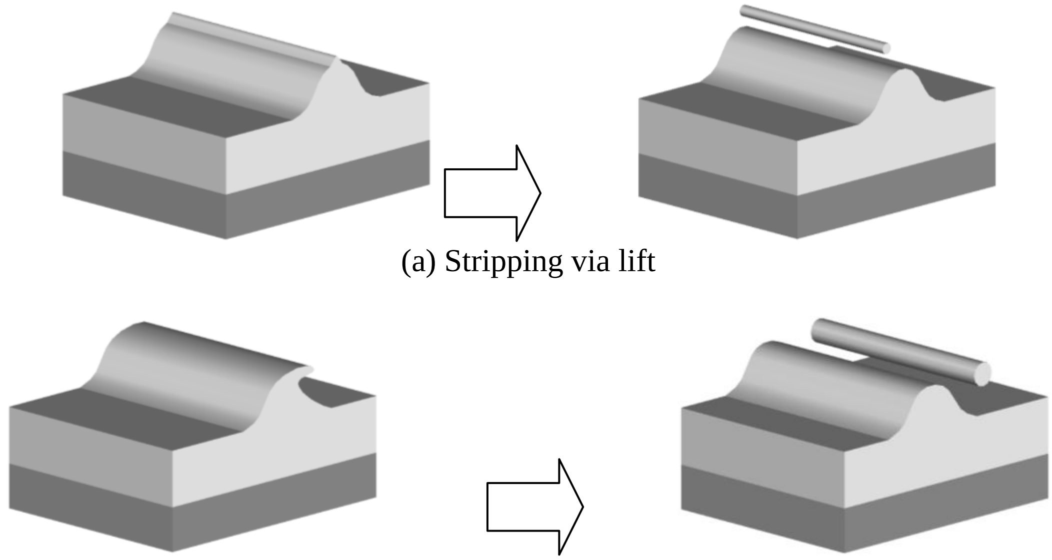


Figure 9



(a) Sheet Perforations (b) Film Perforation

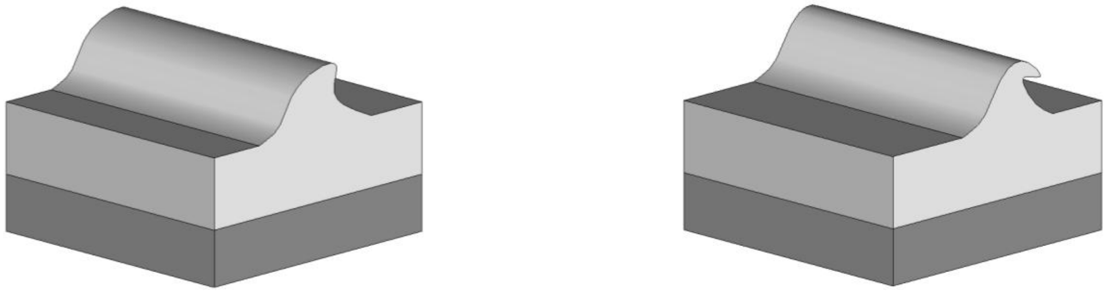
Figure 10



(a) Stripping via lift

(b) Stripping via drag

Figure 11



(a) Spilling Breaker (b) Plunging Breaker

Figure 12

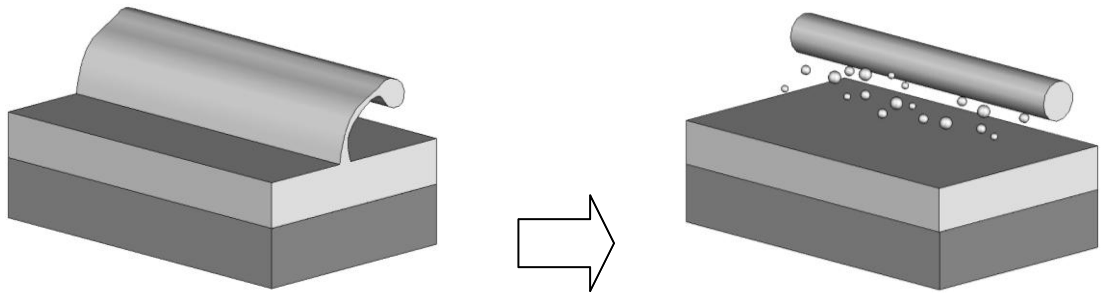


Figure 13

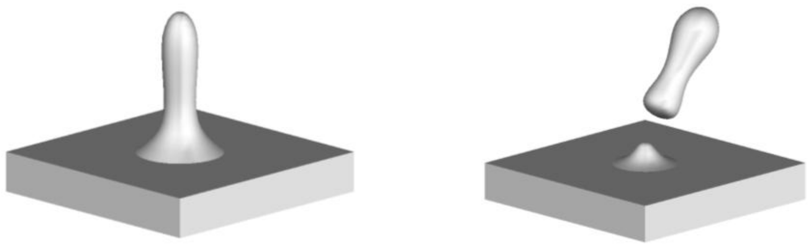


Figure 14

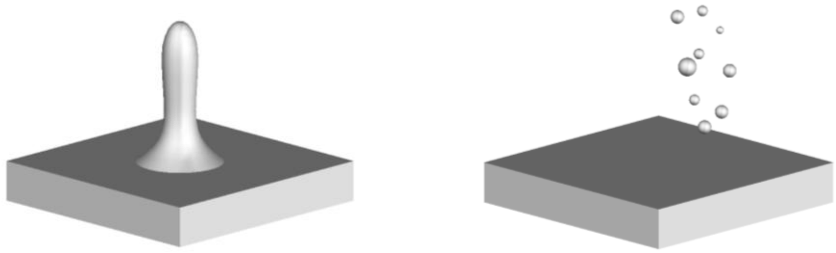


Figure 15

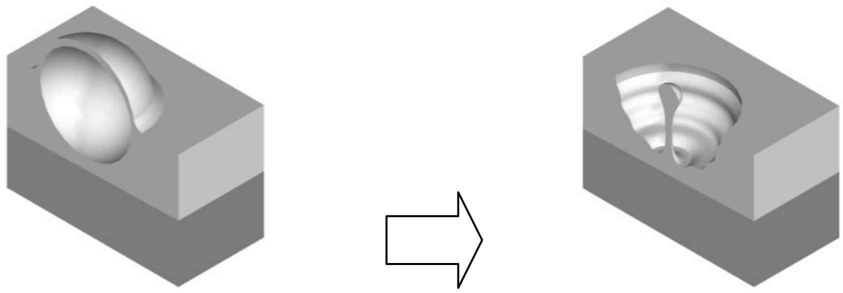
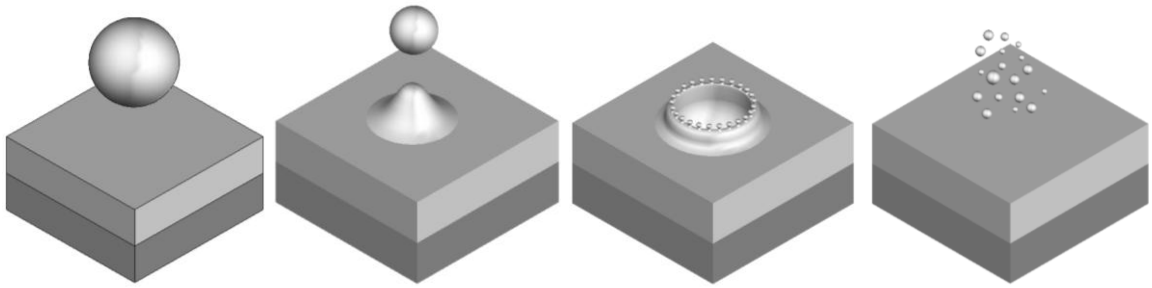


Figure 16



(a) Before Impact (b) Partial Absorption (c) Corona Splash (d) Prompt Splash

Figure 17